PRECISION WORKSHOP METHODS

By

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PREFACE TO FIRST EDITION

THE growth of interchangeable manufacture to its present magnitude has only been made possible by the provision of tools, jigs and fixtures of extreme accuracy. These jigs, etc., must be made within a very small margin of error, so small that special methods are required to make them. Much ingenuity has been expended in devising methods of the necessary precision, with the result that several solutions of any given problem may be available. Each of these may be adapted to certain peculiar conditions. On the other hand, one does sometimes see work being done with difficulty which might be done easily if another plan were adopted.

This book is an attempt to bring together in a convenient form some of the essential ideas upon which precise work depends. These ideas may not always be stated in so many words, but the methods given have been chosen because they show clearly the principles in view, so that they may easily be adapted to other circumstances. A great deal of the matter is based on the notes used for a course in machine shop work for engineering students. In this course the workshops were treated as a laboratory in which the work of the lectures was demonstrated and thoroughly tested, and it has been found possible to give the students a very sound knowledge of the principles underlying machine work. Thus the methods dealt with have not only been well tried in practice but they have been tested under conditions which are in some ways even more searching, and they may be used with full confidence.

Certain chapters have been included which may at first sight appear to be outside the title, for example, those on machinability and limit systems. But the first of these is a very important factor in precise work, since it affects the surface quality, and in consequence the possibility of finishing within fine tolerances. Limit systems are equally important, because upon them depend the much narrower limits within which the tool and gauge maker must work.

It is assumed that the reader has a working knowledge of the usual

machine tools and processes, and no attempt has been made to describe them in detail.

The list of references given at the end of the book does little more than touch the fringe of the publications on precise machine work, but it may be useful to indicate sources of further information to the student.

To Professor F. C. Lea, who first suggested the writing of this book, I am very grateful for his helpful encouragement during its preparation.

My thanks are given to the following firms who have kindly supplied particulars of machines and appliances :—

The B. C. Ames Co. ; Messrs. Buck and Hickman, Ltd. ; The Cambridge Instrument Co. ; The Capstan Gauge Co. ; Messrs. Cooke, Troughton & Simms, Ltd. ; Messrs. Alfred Herbert, Ltd. ; Messrs. Adam Hilger, Ltd. ; Messrs. C. E. Johansson, Ltd. ; Messrs. H. W. Kearns, Ltd. ; Messrs. Loewe-Gesfurel A. G. ; Messrs. L. M. Van Moppes & Sons ; The Van Norman Machine Tool Co. ; The Norton Grinding Wheel Co., Ltd. ; Messrs. J. Parkinson & Son ; The Pitter Gauge and Precision Tool Co., Ltd. ; The Pratt and Whitney Co. ; Messrs. A. Shaw & Son ; The Société Genevoise, Ltd. ; The Taft-Pierce Manufacturing Co.

I desire to thank, also, all those who have assisted me with information, but of whom, unfortunately, I have no record.

H. J. D.

PREFACE TO SECOND EDITION

In this edition a new chapter has been inserted on the subject of Surface Finish, the evaluation of which has been one of the most important and interesting developments of machine-shop work in recent years.

Sundry additions and corrections have been made, for some of which I am much indebted to readers who have been kind enough to send me suggestions.

The references have been supplemented by a number of recent ones to bring them up to the present time.

H. J. D.

PRECISION WORKSHOP METHODS

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CHAPTER I

NEED FOR PRECISION IN MACHINING

THE demand for precision in machining components is extending steadily. Not only are the permitted variations in size diminishing, but the number of classes of work which are made to limit gauge is increasing. Ever since small arms components were made on an interchangeable system there has been a growing realisation that hand fitting is one of the most expensive processes in use in the shops. Along with this realisation there has been a steady improvement in machines and methods, with the result that the cost of machining within narrow limits of size is continually falling. As an example, the centreless grinding machine has been developed to such an extent that one man tending three of these machines with automatic feed and ejection devices is able to produce as much as fifteen men using the older centre type grinding machine. The quality of the work produced by the centreless machine is as good as that done on centres. Two ten-thousandths of an inch is quite a commercial tolerance for centreless grinding, and there are few purposes for which such a tolerance is not fine enough to eliminate all need for hand fitting. Similar advances in output without sacrifice of quality, or even with improvement of quality, could be quoted in connection with other operations.

There has been a greatly extended application of processes for making parts ready for use with little or no machining. Die cast and pressed parts are familiar examples. Although such parts require little machining, the moulds or dies, in which they are made, must be finished very carefully indeed. The more exactly they are made to the specified dimensions the longer it will be before wear of the dies will cause the product to fall outside the required tolerance. Thus a high standard of work in the moulds or dies will lengthen

their life. Spread over the large number of pieces produced the cost per piece need not be high. The tendency of large scale manufacture is therefore continually in the direction of greater precision in the tools and fixtures, because it is found that in this way better components are produced and that the extra cost of the tools, etc., is more than counterbalanced by the savings during assembly. These savings are partly due to the elimination of hand fitting and partl to the avoidance of interruptions in the assembling operations. . factories which work on the continuous flow system several manufacturing lines may converge towards the assembling section. Failure to keep up to the time table in this department may disorganise the whole factory. Therefore expenditure on carefully maintained tolerances may be regarded as a form of insurance against costly delays.

Competition between firms and increasing mechanical knowledge on the part of the buyer is a factor in the gradual raising of manufacturing standards. For example, a motor car which would have been considered quite satisfactory some years ago would now be rejected on account of noise in the transmission system. The power expended in the production of noise is astonishingly small, and the difference in efficiency between a noisy and a silent machine is not necessarily great. But the demand for silent running gears has caused the development of gear grinding machinery to a point at which the use of ground gears is not only the surest, but is also very often the cheapest way of satisfying specifications. In consequence hardened and ground gears are now used in places where the ordinary cut gear was once considered quite good enough. As usual, the improvement in methods has reacted on designs, with the further result that extended use tends to reduce the costs of an initially expensive process.

In discussing the question of precision, it must be kept in mind that the present attitude is very different from that which existed some years ago. Then, it was considered satisfactory, if with a fairly high expenditure of time and skill, machines were turned out with the aid of a great deal of individual fitting. Very good work was done in this way, but costs were high and quantities small.

Interchangeability

Now, parts are manufactured in great quantities with very minute variations from standard size. Cutting speeds and the rate of removal

use of the machine. Although machine frames appear to be stiff, they will yield slightly to an applied force. If the force suddenly ceases to act the frame springs back and will continue to vibrate for a time. Every frame will have a definite time of vibration of its own under such conditions. This is known as its natural periodic time. If a pulsating force of the same periodic time be applied to the frame the amplitude of the vibrations will become very considerable as each renewed application of the force adds its effect to the existing vibration. A surface grinding machine with the wheel or spindle out of balance will produce work with a rippled surface under any conditions. But if the speed of the spindle happens to coincide with the natural period of the frame or other part of the machine, the ripples in the work are likely to be much more pronounced. Similarly in turning, one often finds distinct chatter marks in some part of the work. Turning in most materials is accompanied by intermittent shearing as the chip is parted from the work. As each shear takes place the pressure on the tool changes. For each thickness of chip there is a different distance or length of chip between the successive shears. That implies a different periodic time for the pulsating force for each surface speed of the work. No particular effect is likely to be observed until the pulsations synchronise with the natural period of some part of the lathe. When that happens a very definite vibration will be set up and the surface of the work will be corrugated with chatter marks. Once the synchronous state of vibration is reached, the vibrations appear to control the spacing of the successive shearing actions, which will become wider if the surface speed of the bar is raised. This control will persist until a limiting value of the spacing is reached, when the pulsating force will fall out of step. In one particular case chatter began when the surface speed of the bar was 40 feet per minute. The periodicity of the vibrations was observed to be about 2,100 per minute. The speed of the bar was gradually raised from 40 to 90 feet per minute. Other conditions were not changed, but the vibrations remained at 2,100 per minute. The chatter marks on the bar became proportionately longer in pitch as the speed rose towards 90 feet per minute. Beyond 90 feet per minute the chatter died away and the cut was smooth. The pulsations of the cutting force were then evidently well away from the synchronous speed. This illustrates one of the advantages of the new cutting alloys, namely, that they permit much higher cutting speeds and may enable us to keep right out of the chattering range.

Synchronism

The problem of sympathetic vibrations of machine parts is difficult to solve, but if the periodic time can be found it is usually possible to trace the vibrations to the member which is causing them. Very often some badly balanced rotating part is responsible. The remedy is then obvious. At other times where a pulsating force, not due to lack of balance, synchronises with the natural period of some machine member it may be possible to change the periodic time of the force or, alternatively, to alter the mass or stiffness of support of the machine part so that its natural period will be different. One is often tempted to attribute chatter marks to defective toothed gearing, but investigation rarely shows any connection between the number of teeth engaged per minute and the number of chatter marks per minute.

The simple vibration indicator shown in Fig. 1 is very useful for observing vibrations. It consists of a number of spring wires held in a clamp and loaded at their free ends. By changing the free length of a spring it may be tuned to vibrate at any required speed. Tuning is easily done with the aid of a variable speed electric motor with rheostat. A small weight clamped to one side of the motor shaft will set up vibration in the motor frame or supporting stand.

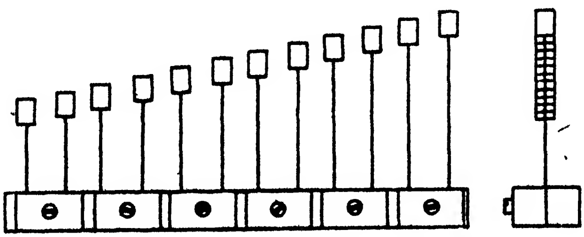


FIG. 1.

The period of this vibration is dependent on the speed of the motor and is therefore easily controlled and measured. When the arrangement of Fig. 1 has been tuned each spring will have a known period of vibration, and when the clamp is held on a vibrating part the particular spring which synchronises will respond quite clearly and definitely. It will sometimes happen that the speed of vibration of the machine will fall between the periods of two springs. Both will then respond unless the gap between their periods is too great. The

vibration indicator shown will cover the range from 1,000 to 2,500 per minute, but it is intended for use in preliminary experiments. It should be used in conjunction with indicators of smaller range, covering a range of 300 or 400 vibrations per minute. These should be applied when the vibration has been approximately located. It will be found that definite knowledge of the periodicity of a vibration is of great help in locating the cause.

There is another type of indicator in which the free length of a single spring may be varied by a slider moving along a scale graduated in vibrations per second. The slider is adjusted until the system comes into tune with the unknown vibration, when the frequency may be read off the scale directly.

Torsional Oscillations

In connection with vibration, it may be remarked that torsional oscillations in the driving shafts of milling machines have been held responsible for poor finish in milling operations. To remedy this flywheels are fitted to the main spindles close to the cutters, so that the effects of varying resistance are smoothed out as quickly as possible and impulses are not transmitted backwards to other shafts and gearing.

A point which has sometimes been overlooked by machine tool designers is the value of masses of metal, well above the requirements of strength, in checking vibration. Cast iron for machine tool parts has good qualities of its own in addition to the convenience with which it can be cast into the shape desired. One of these is the excellence of the wearing surface which it acquires when suitably proportioned to the load. Another good quality is its tendency to damp out vibrations rather than to maintain them. In view of the growing use of welded structures of steel, it is well to bear this point in mind. A steel frame might be fully strong enough for a machine tool, but on account of its readiness to vibrate might be entirely unsuitable.

Specification of Limits

With regard to the limits which are specified on drawings, it may be said that there has been, and probably still is, a tendency to set these too closely. This is especially true of the final product in which very close fits are often not necessary. In such cases it is merely

necessary to specify limits which will ensure ready assembling. These should be chosen with that object in mind and need not be close. If needlessly small tolerances are specified, one or other of two things will happen. If the tolerances are rigidly enforced the product is more costly than it should be. If they are not enforced the whole system will eventually become slack and all limits will tend to be ignored.

Comparatively wide limits for the product may quite reasonably be associated with fine limits in the tool and gauge-making departments. Tools and gauges are made to deal with large numbers of parts. Therefore they should be made near to size so that manufacturing limits are not cut down by latitude in the tool room. That is why the precision demanded in tools and fixtures often appears to the casual observer to be out of proportion to the quality of the final product.

CHAPTER II

INTRODUCTION OF LIMIT SYSTEMS

Some thirty or forty years ago the idea was very widely held that to manufacture components within specified tolerances implied a deliberate sacrifice of quality. It was commonly thought that the ideal method was to make one part fit another, which had already been finished to size. A fit of this kind was supposed to be of the highest possible quality, and it was not generally admitted that many different grades of fit, actually all performing the same function quite satisfactorily, resulted from this process. It has gradually come to be realised that where so much is left to the judgment of the individual workman there would be nearly as many kinds of fit for any particular purpose as there were workmen.

Most of the fits made in this way worked satisfactorily. But realisation of the variations was inconsistent with the idea of one perfect fit for each particular job. By careful measurement it has been possible to specify a range of sizes within which parts will work well enough for their intended purpose, and there is no longer any need to strive for useless accuracy or to depend upon a guess. Experience of satisfactory workmanship is now recorded and is available in the various tables of limits.

Distinction between Tolerance and Allowance

The present-day problem is very largely the choice of the most suitable tolerance for each class of work. At this point it may be well to point out that " tolerance " is defined by the British Standards Institute as " A difference of dimensions prescribed in order to tolerate unavoidable imperfections of workmanship." Tolerance must not be confused with " allowance," which refers to a deliberate difference between the dimensions of two fitting parts to allow for various classes of fit, *e.g.* to allow clearance for lubrication or interference for holding two parts tightly together.

The word unavoidable in the definition of tolerance is not to be read in an absolute sense, but rather as " unavoidable, consistently with reasonable cost of production for the kind of work referred to."

For example, it must not be taken to mean that the wide tolerances used in the manufacture of agricultural machinery represent absolutely unavoidable imperfections of workmanship. It would, however, be more costly to work to smaller tolerances and such extra cost would give no compensating advantages, but would rather tend to make the product unsaleable. In other words, within the limit of price it would not be possible to manufacture to smaller tolerances. It is in this sense that "unavoidable imperfections of workmanship" must be understood.

The distinction is an important one, because, where price and time are not important, tolerances may be as small as we care to make them. In making high-class gauges it is not unusual to keep within a few millionths of an inch of the specified size. But such accuracy is costly, and for many purposes would not result in a more efficient or better machine. For each particular job there is probably an ideal tolerance, in deciding which the following considerations must all be given due weight. The ideal tolerance for any particular purpose is that one which will ensure satisfactory operation at the least cost. Cost must be considered as cost per unit of operating time. Up to a certain point smaller tolerances mean longer life and may therefore reduce the cost per unit of operating time. Beyond this point, lower costs may be reached by reliance on cheap replacements. This is one of the advantages of interchangeable manufacturing, which depends upon working to specified, but not in all cases, small tolerances.

Even where parts do not fit one another and need not therefore be made closely to a size, it is advisable to specify the limiting dimensions in order to avoid waste of time in finishing more carefully than is required. Some firms adopt the system of dimensioning such parts in vulgar fractions, eighths and sixteenths, while they reserve decimals for the specification of dimensions with smaller tolerances. Other firms adopt a common system for all dimensions, but specify a tolerance of ten to twenty-thousandths of an inch for the unimportant dimensions.

Advantages of Interchangeable Manufacturing.

The main objects to be gained by interchangeable manufacturing were :—

1. To reduce costs by standardising and improving methods of manufacture by production in batches rather than as single parts.

2. To reduce the handwork and time required in assembling.

3. Later it appeared to be a great advantage to be able to secure replacements without delay and at comparatively small cost.

The last item now tends to overshadow the other two, important though these are. Complete interchangeability is not essential to obtain objects 1 and 2. It is possible, when components are gauged, to separate them into groups of similar dimensions. Provided suitable groups are brought together in the assembly department there need be no difficulty at this stage. It is often much cheaper to grade parts according to size than to make them within very close limits. The quality of the assembled article does not suffer by this procedure, although it may not be possible to replace components of the assembly. This, however, is not always a disadvantage, since the whole assembly may be counted as a unit in a complete machine, and owing to the method of manufacture it may be less expensive to replace the assembly than it would be to insist on complete interchangeability of its elements. The only dimensions which then require complete interchangeability are those external ones where the assembly comes into contact with other parts. These dimensions may not need to be kept within the same fine limits as the interior ones, but even though it may be necessary to insist on very fine limits for the external dimensions, the number of surfaces involved is less.

Selective Assembly

The method of selective assembly discussed above is exemplified in the manufacture of ball bearings. The variations in size, which make the difference between a tight or a slack bearing, are very small. Even in the simplest kind of ball bearing three surfaces are involved, namely, the inner race, the balls and the outer race. Variations of the order of one ten-thousandth of an inch are important, and the cost of manufacturing within such a tolerance would be excessive. Hence complete interchangeability between the elements is abandoned and they are graded into groups and assembled accordingly. Incidentally this method makes it a simple matter for the manufacturers to supply bearings which are suitable for various purposes. For example, there is a free running bearing with slight shake for applications where some freedom is required, next there is a bearing which is free but without appreciable shake for the average case, and finally there is a bearing which is assembled with a slight initial load for use where perfect freedom is less important

than complete absence of shake. This latter finds a use in machine tool work, where exact constraint of a shaft or spindle is of primary consequence. Applications to machine tool spindles usually require a bearing which is well above its work for other reasons. Thus any effect of the initial load in shortening the life of the bearing is of no importance. It is, however, debatable in many cases whether the pre-load does actually increase the working load.

The question of selective assembly as an alternative to full interchangeability is easily settled in most cases quite definitely for or against. When the answer is not so clear it becomes a matter of balancing the cost of scrapping components which may be only partly worn out against the cost of manufacturing all the components with finer limits.

There is another question which may appear to be somewhat academic, yet it has a very serious practical bearing. The question is, "How far is similarity essential?" Perfect interchangeability would involve close similarity throughout nearly all dimensions of like parts, if such parts were being made quite independently to gauge in two different factories. Otherwise different methods of manufacture might result in certain uncontrolled surfaces being used for location at one factory, with the result that the parts from the two factories might differ in important dimensions or in the relation of one surface to another. Co-operation between factories will often be found to avoid the need for an expensive degree of interchangeability without detriment to the product. The principal items in co-operation are the use of the same locating points or surfaces and similar methods of gauging.

Choice of Tolerances

But in the great majority of manufactures the need for selective assembly in order to ensure sufficiently close working fits does not exist. In general, the selection of a suitable tolerance may be discussed as follows.

There is for any particular shaft and bearing a minimum clearance, which will just avoid risk of seizure. This will provide room for lubrication and a margin for possible change due to differential expansion of the two members with change of temperature. There is also for the same bearing a maximum clearance. If this be exceeded the parts will not be guided closely enough to do their work with certainty. Starting with the minimum clearance, the shaft and

bearing gradually approach the latter condition as wear takes place. Thus the longest possible working life of the parts would be ensured. But it could only be done in one or other of two ways. Both parts must be made dead to the size specified. Or, one part having been made, the other part must be made to the size of the first part plus or minus the allowance for clearance according to which part had been finished first. The tolerance on at least one part would have to be zero.

But even to approach zero tolerance is extravagantly costly and better service may be given by the adoption of reasonable limits, since thereby replacements may be made at moderate cost. Tolerances provide an example of the working of the law of diminishing returns. Each successive outlay, beyond a certain point, to reduce a tolerance brings in less return, that is, less extension of the useful life of the part considered.

It is, on the other hand, possible to make tolerances too large, in which case little advantage is gained in reducing machine costs, while there may be difficulty in assembling. At this stage handwork is the principal charge, and the extra time spent in selecting or rectifying unsatisfactory parts is usually far more costly than the adoption of narrower limits of manufacture.

Importance of Surface Quality

Another point to be considered is that tolerance must bear some relation to the quality of the surface. It is of little use to specify small tolerances if the methods of machining are such as to produce rough surfaces. The effect would merely be that the higher parts of the surface would lie within the tolerance while the greater part of the surface would be outside the limits. Such a surface would have a very short life before it would become unserviceable through wear.

To illustrate this point, take the case of a cylindrical plug gauge. If this be finished by grinding its original dimension will be the dimension given by scattered high points. These are a small proportion of the total surface and are quickly worn down below size. If a similar gauge were finished by lapping, the area of the high spots would form a much greater proportion of the whole surface and the life of the gauge would be correspondingly greater. Even in carefully lapped gauges of the Johansson type, which may be wrung together, it is found that the rate of wear owing to the first few wring-

ings is very much higher than the rate for later wringings. This suggests that even these very nearly perfect surfaces have at first high places which wear down by contact with each other. Ground finishes, examined with the aid of a microscope, have the appearance of overlapping or interlocking furrows. The initial loss of size when such finishes are used for working surfaces is comparatively rapid. There is the even more serious consequence that the oil stream is contaminated with particles of metal which cause wear in other parts of a mechanism. It has been said that an electro-magnet introduced into the lubricating oil of a petrol engine, undergoing its preliminary test, will pick up an astonishing quantity of steel particles, even in good class work.

It is clear that as a means of increasing the working life of a part,

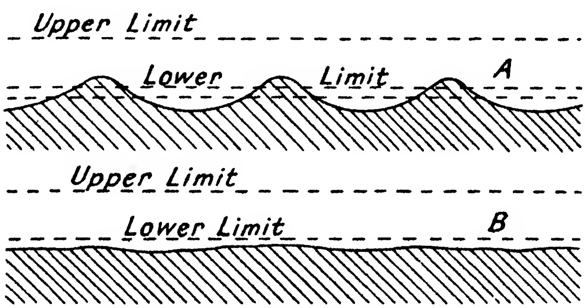


FIG. 2.

the surface finish may be of greater importance than the nominal tolerance. A surface shown in cross-section at A, Fig. 2, in which say twenty per cent of the total area consisted of high spots lying within the tolerance limits might be less satisfactory than a surface as shown at B, in which ninety per cent of the area lay just below the bottom limit while the remaining ten per cent was lower still. The few high spots in the first surface would soon wear down while the large area in the second surface would suffer little change. Surface A would be well below the level of surface B before the areas in contact were equal. Although slightly loose at first the fit of the latter surface would remain fairly constant. To emphasise the importance which surface finish is now assuming, it may be mentioned that ground finishes, which were considered good enough at one time, are now being followed by fine grinding or lapping. Surface finish is considered more fully in Chapter XIV.

The Cost of Accuracy

The cost of maintaining small tolerances depends very much on the method of machining, that is, on whether the work is turned, bored, threaded, ground or lapped. To the demand for higher quality there is a continual response in the way of improved methods. As an example of improved methods, it is now possible to cut better screw threads with a die-head than some which were used as gauges about thirty years ago. It is therefore difficult to discuss the relative costs of various grades of tolerance with any confidence that

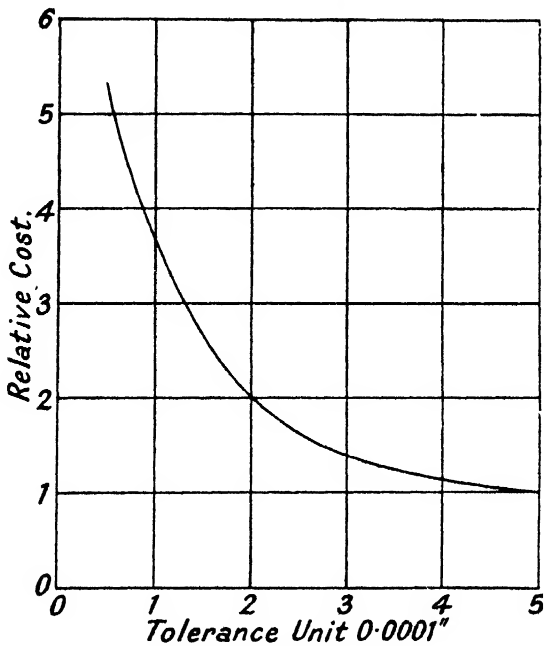


FIG. 3.

what is written will remain true in detail for any considerable time. But the principles affecting the matter are less likely to change, and it is to them that attention will be directed.

The curve shown in Fig. 3 is derived from values given by W. E. Harrison, Chairman of the A.S.M.E. Sub-committee reviewing tentative U.S.A. standards for tolerances and allowances for cylindrical parts and gauges. The process is grinding, and it will be observed that the relationship between accuracy and cost is hyperbolic in character.

It should be remarked that in practice there would be a change in the method of production for tolerances below two ten-thousandths of an inch. Down to that point the parts would be ground. Below it they would usually be finished by lapping. This process gives a finish which until recently has not been possible by grinding. Lapping still remains the accepted method for fine finishing, but it is now possible to use an exceedingly fine grained abrasive wheel which will produce a quality of surface almost as good as that obtainable by lapping. Economy of time is claimed for the process, but the mechanical lapping machine has been developed to such an extent that there seems little possibility of saving in that direction. Machines are in use for lapping gudgeon pins within $\pm 0{\cdot}00005$ inch of the specified diameter at the rate of 140 pins per hour per machine. Lapping is restricted to simple plane, cylindrical and conical forms, but designs may be adapted to take advantage of the expansion process for building up these simple forms into more complex parts. The expansion process referred to above depends on cooling the inner member by means of solid carbon dioxide or liquid air to a temperature of $-123°$ F. In ordinary steel a contraction of nearly a thousandth of an inch per inch of diameter is possible. This is sufficient for the assembly of a satisfactory interference fit for many purposes. If greater interference is required the outer member may be heated in hot water up to about 200° F., which will almost double the permissible interference. This method of assembling does not permanently affect the parts, and it is likely to be used more generally as its possibilities become more widely known.

Referring again to the cost of fine tolerances, the following example is taken from end gauges of the Johansson pattern:

Accuracy	*Relative Cost*
8 parts in 1,000,000	100
5·5 ,, ,, 1,000,000	123
3 ,, ,, 1,000,000	163

The different grades mentioned are not made by different processes. It is possible that the finer grades are not the result of extra care, but that they are selected from a large batch of finished gauges. The costs, or rather the prices quoted, are however a rough indication of the proportion of the finer grade pieces which occur, and to that extent are a guide to the cost of production.

Tolerances in Various Machining Operations

Considering work which is finished by turning in a turret or other lathe of that class, the cost of maintaining specified tolerances depends upon the time spent upon re-sharpening and re-setting tools. During the process of re-setting the machine is idle. Fine tolerances require more frequent tool-setting than coarse ones. In addition each setting takes more time, since it must be done with greater care in order to keep closely to the lower limit of size initially and thus take advantage of the full tolerance before the tool must be re-ground and re-set.

The cost goes up more rapidly than in direct proportion to the narrowing of the limits. If, for example, a tolerance were to be reduced from two to one-thousandth of an inch the tools would have to be re-set more than twice as frequently. Experience indicates that for the halved tolerance the number of settings would be nearly three times as great as it was for the initial tolerance.

In automatic screw machines and turret lathes it is possible to work within a diameter tolerance of three-quarters of a thousandth of an inch and a length tolerance between two and three-thousandths of an inch if the traverse stops are used. Where lengths depend on a formed tool carried on the cross slide the tolerance may be reduced to little over one-thousandth of an inch. In multi-spindle machines diameters cannot be held quite so close as the limit mentioned above, on account of indexing variations. Beyond a certain point the cost of maintaining fine tolerances by turning in the usual way becomes so great that other methods of finishing may be more economical. If the work can be transferred to a grinding machine for the final reduction costs will be lower, or bearing in mind what has been said about the quality of surface in relation to tolerance, grinding may only be an intermediate process to be followed by lapping. There is now an altered method of turning by which even better results may be secured. This followed the introduction of the carbide tool. It is an excellent example of more severe specifications inducing a change in methods, which eventually produces the needed results without proportionately increased costs.

Assuming for the moment that a ground surface may be considered good enough, the value of the grinding machine arises from the property of automatic renewal of cutting edge of the grinding wheel. As grains become blunted they are torn out of the wheel by the increased load which is a consequence of the bluntness of the cutting

edge. The wheel is very gradually diminished in size but retains its sharpness because new sharp grains are being brought into action as the used grains are discarded. No time is lost in removing the tool for re-sharpening. All that is needed is a small in-feed of the wheel from time to time to compensate for the loss of size. This alteration of the feed is merely a part of the ordinary process of grinding and involves no expenditure of time.

Comparing the grinding wheel with the ordinary turning tool as a means of finishing to size, there are several points in which the former has the advantage. Suppose, for instance, that a piece is almost to size and that a finishing cut is taken, which by some mischance leaves the work about one-thousandth of an inch over size. It will be found quite troublesome to remove the last thousandth with a turning tool. Probably the tool will have to be specially sharpened, and even then may not cut uniformly if the work is at all hard, and especially if the hardness is irregular. In taking such light cuts, variations in cutting pressure, caused by loss of sharpness or by uneven quality of material, exert a great influence on the depth of cut. A very slight change may push the tool right away from the cut. Contrasted with this, the grinding wheel is composed of cutting grains which are normally much sharper than the ordinary turning tool, and it is easily able to take very light cuts with certainty. One-eighth of a thousandth of an inch is quite a usual depth. Abrasives used in grinding are much harder than tool steels, and such variations as occur in the hardness of the work are very small in comparison with the difference in hardness between the work and the cutting grain.

It is considerations of this kind which have brought the grinding machine to its present position as a means of finishing to size, especially where tolerances are small. Something must be attributed also to the attention which has been given to the development of the machine, whereby it has been rendered less and less dependent on the skill of the operator.

Some of the items, which have been discussed above in connection with the grinding wheel, have a bearing on the new cutting alloys, and on the use of diamond tools for sizing and finishing. Both these classes of tool are exceptionally hard and resistant to wear and are able to maintain keen cutting edges for long periods. They are especially good for soft metals which are not suitable for the grinding process.

Failure of Tools

A distinction may be drawn at this point between the way in which wear takes place in a roughing tool and the way it takes place in a finishing tool. When a turning tool is taking a moderately heavy cut in a tough material the actual cutting edge is only lightly loaded. The greater part of the pressure of the chip acts on the top surface of the tool at some distance behind the cutting edge. The chip is stiff enough to resist the bending action of the tool and it transmits force backwards to the bar.

As a consequence, the chip begins to split away from the bar at some distance above the tool face. Fig. 4 shows diagrammatically the action. In this figure the triangular area *a*, *b*, *c* represents what is probably at first an empty space, but is later filled with part of the chip which under heavy pressure spreads on the top face of the tool and flows into the triangular cavity to form the built-up nose about which there has been some controversy. Exactly what occurs is even now not very clear, but there is no doubt that when a tool, which has been cutting heavily, is carefully removed from the cut there may be found a small wedge-shaped piece of steel strongly adhering to and continuing the top face of the tool.

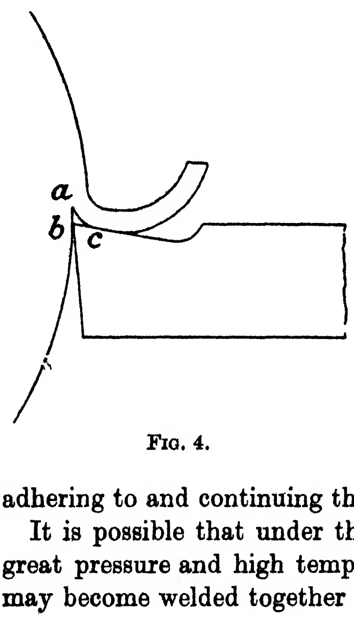


FIG. 4.

It is possible that under the conditions of heavy cutting, namely, great pressure and high temperature, particles of the steel being cut may become welded together and firmly attached to the tool nose.

The Built-up Edge

The built-up edge is much more noticeable with high-speed steel tools than with carbon steel tools. Whether this is due to some difference in the surface quality of the steel or to the very much greater temperature reached when cutting with high-speed tools is not known. It is of interest that some, at least, of the new cutting alloys of the carbide class do not appear to form the built-up edge. This is in spite of the fact that they may be run through a range of speeds much

greater than those possible with high-speed steels and including even higher temperatures. Therefore temperature alone cannot be the factor which controls the formation of the built-up edge. It is likely that some peculiarity of the surface of the tool is more important.

The question is of more than abstract interest, because there is no doubt that some tools give a better finish than others. Carbon tool steel has often been preferred for finishing cuts, because it appears to produce a smoother surface than high-speed steel. Tungsten carbide is liable to form a built-up edge when machining ferrous materials and in consequence other carbides, e.g. titanium and tantalum, are preferred for finishing since they appear to be relatively free from the tendency and produce a better surface.

Quality of Machined Surfaces

When cutting dry a carbide tool leaves a smooth bright surface, which is conspicuously different from the surface left by a high-speed steel tool. This may be due to the absence of any tendency to build up a false edge on the carbide tool or it may be due to the presence of a keener cutting edge, or possibly to some other as yet unexplained cause. But however it may be accounted for, the built-up edge is believed to be of very great importance, especially in connection with finishing cuts and small tolerances. In the foregoing discussion reference has been made chiefly to roughing cuts, because the built-up edge is greater under roughing cut conditions and therefore more easily studied. The same action occurs in the case of finishing cuts to an extent which depends upon the material of which the tool is made. When it forms, it may at times cause a tool to cut below the size for which it was set. Alternate building up and dislodgment of the edge may then be very troublesome when limits are fine.

In light cutting the main pressure comes very close to the cutting edge, thus concentrating the wear on the very small part of the tool near the extreme edge. As it is upon the extreme edge that the maintenance of size depends, the value of the cemented carbide class of tool is obvious. This kind of tool has the properties of great hardness and very high resistance to wear.

There is a distinct difference between the breakdown of a tool taking a roughing cut in tough material and that of a tool taking a light finishing cut. The difference is less marked in brittle material.

If a roughing cut in a tough material be continued until the tool

breaks down, the cause of failure will as a rule be traceable to the breaking away of part of the cutting edge.

Figs. 5, 6 and 7 show successive stages of the process which leads to the final breakdown. Fig. 5 is a view of the tool as it begins to cut; Fig. 6 shows the formation of a groove in the top face of the tool; Fig. 7 section shows the groove much later, as it appears just before the triangular piece ABC breaks off; and D shows the final

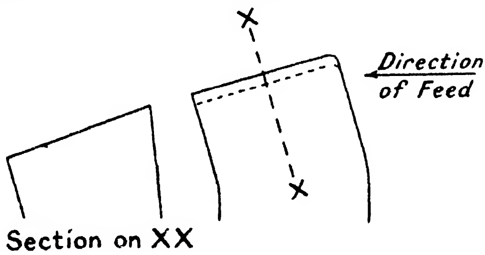


Fig. 5.

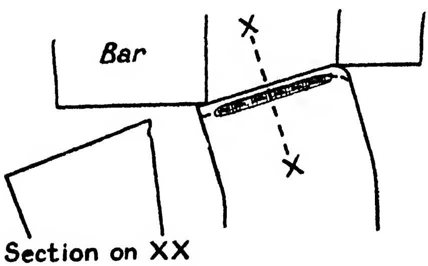


Fig. 6.

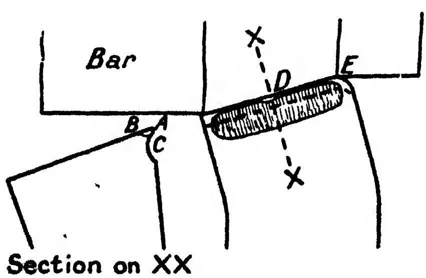


Fig. 7.

state in plan. If the piece ABC includes any serious proportion of the cutting edge the tool will cease to cut, although if ABC is only a short part of the edge, as in Fig. 7, it is possible for cutting to continue. In the latter case there is heavy rubbing between the work and the broken face of the tool, but the separation of the chip at that place is accomplished by forces transmitted from the chip at each side of the break, where cutting continues normally. The finished size of the bar will be maintained until the edge at E, Fig. 7, wears. The chip at this point is thin, and wear is slow in comparison with that due to the full thickness. Hence the edge at E usually endures until after breakdown of the more heavily loaded part of the tool.

A finishing tool, on the other hand, fails by gradual wear of the

extreme cutting edge. When working within fine limits a tool may have to be reground and reset even though it may be sharp enough to continue cutting. Resistance to local wear is then of more importance than ability to resist large forces or shocks. Thus both high-speed steel and the special cutting alloys continue to be used, each having its own field. Both are still under experiment, and improvements are being made. It seems likely that at the time of writing we are near the beginning of a period of change in shop practice as great as that which followed the introduction of high-speed steel.

Diamond Tools

Contrary to what might have been expected the special alloys have rather stimulated than discouraged the use of diamond tools for finishing purposes. Diamonds have been known and appreciated as cutting tools to a limited extent for years. But their initial cost is high, and as their possibilities were not well known, few people considered them a profitable investment. The special alloys are also expensive, but much less so than diamond tools. They have therefore been tried where the diamond tool would not at first have been considered, and have formed an introduction to the even greater possibilities which the diamond has in its own special field.

Summary of Finishing Processes

The following notes are intended to present some idea of present-day possibilities of different processes. It must be repeated, however, that there is a very great deal of experimental work going on, so that further progress may occur at any time.

Grinding for many years was regarded as the best finishing process for all work except the very finest, such as gauges. For many purposes the centreless type of machine has now replaced the older centre type, in addition to opening up new fields for grinding. Tolerances as fine as those of the centre type of grinding machine are commercially possible with the centreless machine on work which is quite outside the range of a centre type machine. For instance, a bar 3 inches in diameter and 20 feet long can be ground on a centreless machine within 0·0002 inch of roundness and with a diameter variation not exceeding 0·0005 inch for the whole length. This is done with a wheel of 24 inches diameter and 6 inches face width. The use of these machines has directed attention to what are known as constant diameter figures. These are figures of a lobed form, not circular. It is found that under some conditions the centreless grinder is liable

to produce such lobed cross-sections in the work. The matter is discussed more fully in Chapter XIII.

Tolerances of the order of 0·0002 inch or less are usually produced by lapping or honing when the work has been ground. As already pointed out, the lapped surface is more perfect and therefore more durable than a ground surface of equal nominal tolerance.

Finishing by means of carbide tools is now sometimes done in place of grinding or grinding and honing.

The following examples show the kind of cuts which are taken by the cemented carbide tool in cast iron. At one works petrol engine cylinders are bored with a tungsten carbide (Wimet) tool at 130 feet per minute cutting speed and a feed of 0·015 inch per revolution. At this stage 0·015 inch is left on the diameter to be finished by grinding, which leaves the diameter 0·0005 inch undersize for the finishing operation of honing.

Another firm has abandoned the method of grinding and honing to finished size in favour of finishing by boring tools of cemented carbide. The cylinder, which is for an air-cooled internal combustion engine, is faced on the flange and bored in a turret lathe, the bore being left about 0·008 inch small. It is then rechucked, being located from the already faced flange, and bored by a cemented carbide tool at a cutting speed of 400 feet per minute, and a feed of 0·002 inch per revolution. After this process the bore is parallel and circular within 0·0002 inch.

Very good finished surfaces are obtainable with cemented carbide tools, especially if care is taken in finishing the cutting edges. These tools are used with very light cuts and fine feeds, and the chips are so fine that no tearing takes place ahead of the cutting edge. Consequently the surface finished by them is good or bad according to the quality of the edge. The finer and better the edge the smoother is the finished work. Taking advantage of this fact, it is now becoming usual to lap the cemented carbide tools with special diamond laps whereby they are brought to an almost perfectly smooth edge. A tool prepared in this way will finish a cast iron cylinder bore in a manner which some consider to be superior to grinding and honing. For this reason fine boring with carefully finished cemented carbide tools is adopted by some firms as a finishing process, even though it shows no saving in time in comparison with grinding and honing. For this kind of work special boring machines are used.

As an instance of a finishing cut in non-ferrous metal, phosphor bronze bushes are bored at 900 feet per minute cutting speed and a

feed of 160 revolutions per minute. The bores are cylindrical within 0·00025 inch.

For taking light finishing cuts in non-ferrous materials the diamond tool is frequently used. Although its first cost is high, its endurance is very great, it is able to cut at very high speeds, and it produces a finished surface which can hardly be equalled by any other method. Even the cemented carbide tool is scarcely able to produce an equally good surface finish, although when due attention is given to the cutting edge it is able to approach very nearly to the diamond tool in the quality of its work. The objection is sometimes raised that non-ferrous metals are likely to retain particles of abrasive grit if finished by grinding. This is particularly objectionable if the surfaces are on working parts, hence it is commonly preferred to finish such parts by turning or boring. Incidentally the surface turned by a diamond or cemented carbide tool is smoother and more nearly perfect than a surface which has been ground. The following figures which were supplied by Messrs. L. M. Van Moppes are typical of the practice of firms using diamond tools.

Material.	Work.	Revs. p.m.	Ft. p.m.	Depth of cut.	Tolerance.	Coolant and lubricant.	Feed.
Bronze.	Boring little end of connecting rod.	2,000–3,000	—	0·005″	±0·0001″	Mineral, lard, oil and soda water.	0·0013″
Babbit.	Boring big end of connecting rod.	1,500–2,500	—	0·010″	±0·0001″		0·0023″
Aluminium.	Piston turning.	—	200–1,000	0·010″	—	Solution of soap and water.	
,,	Boring gudgeon pin holes.	—	200–1,000	0·010″	—		
,,	Crank-shaft main bearing housing (2·812″ dia.).	1,680	1,240	0·0075″	—	None used.	0·0013″
,,	Camshaft bearing housing (2·625″ dia.).	1,750	—	0·005″	—	None used.	0·00125″
Tin base alloy.	Number ring for odometer (0·8425″ to 1·0625″ dia.).	6,000	—	0·004″	—	—	0·0005″
Ebonite.	Various.	3,000	—	0·0005″	—	—	

A diamond tool is shown at A in Fig. 8. It is found that the best top rake for a diamond tool depends on the material to be cut very

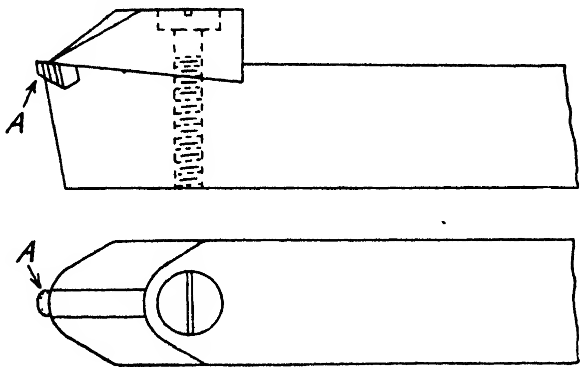


FIG. 8.

much in the same way as ordinary tools. For turning aluminium 5 degrees positive rake works well; for bronze 2 to 3 degrees negative rake is most effective.

The Relation of Cutting Speed to Surface Finish

This is a matter of great importance in finishing cuts. Until comparatively recently the range of speed permissible with ordinary cutting tools has not been great enough to indicate the interdependence of finish and cutting speed. Within the limits of the cutting materials available there was little change in surface quality as speed was raised, except that above a certain very moderate speed it was not possible to ensure a good finish. This, as was suggested above, may have been due to the building up of a false edge on the tool.

It was not possible to proceed beyond a moderate cutting speed, and such alloys as were suitable for that speed were very liable to develop the built-up edge. Since the introduction of the cemented carbide type of cutting material much greater speeds have been used, and it has been observed that the surface finish improves as the cutting speed is raised.

Under given conditions the surface depends upon the material of the tool. A high-speed tool at a given speed within its range leaves a distinctly rougher finish than some cemented carbide tools. But as the cemented carbide tools are run at still higher speeds, going right beyond the present range of high-speed steel, the finish becomes even better. That time is a factor in chip formation may be seen

very clearly by starting a cut on a medium steel bar at low speed, say 10 feet a minute, and gradually raising the speed until it reaches 200 or 300 feet a minute. At low speed the chips leave the tool in short separate segments which become less completely separated and less sharply curved as the speed rises, until at the highest speed they are quite continuous and almost straight. Accompanying the change of form is a reduction in the power required to remove a given weight of metal per minute as the speed rises. These facts are of interest in connection with the machinability of the steels which are most liable to work harden. Their bearing in that connection is discussed in the next chapter.

Depth of Scratches in Finished Work

By forming a tangential optical flat on the surface of cylindrical work to be examined, of a depth such that no scratch is quite continuous across the centre, the depth may be calculated. Mr. W. G. Collins of the Cambridge Scientific Instrument Co. developed the method which is diagrammatically shown in Fig. 9. Measurements obtained by this method on the scratches left by grinding with a 500 grain wheel gave depths varying from 0·0004 to 0·00073 millimetre (0·000016 to 0·00003 inch). For comparison the scratches left by a normal ground finish varied from 0·00148 to 0·00215 millimetre (0·00006 to 0·00008 inch).

Machining allowances are an important factor in production, and they may be greatly affected by the method of machining. When a casting is to be machined by the usual cutting tool it is necessary to provide such allowances that the tool will get well under the skin of the casting. In this way the hard skin will be broken off without greatly affecting the cutting edge, especially that part of the cutting edge which produces the finished surface. The allowance to ensure this must be fairly generous, much more so than it need be if the surfaces are to be machined by grinding. For this reason the grinding process, although at first sight more expensive, may be a cheaper method if due care is taken in the provision of suitable allowances. The important factor is, of course, that the cutting edges of a grinding wheel are not ruined if they should come into contact with the scale.

The present position in reference to tolerances may be summed up as follows. The general run of medium to light work is covered by tolerances between one and five-thousandths of an inch. A fair proportion of light work is kept to a tolerance of three-quarters of a

thousandth of an inch. Tolerances as small as two ten-thousandths of an inch may be required for some purposes, but unless these are on simple forms suitable for grinding or lapping they will be expensive and should not be specified unless they are essential to the proper working of the product.

Milling is a process capable of high rates of output but can only be used for tolerances below two thousandths of an inch by the

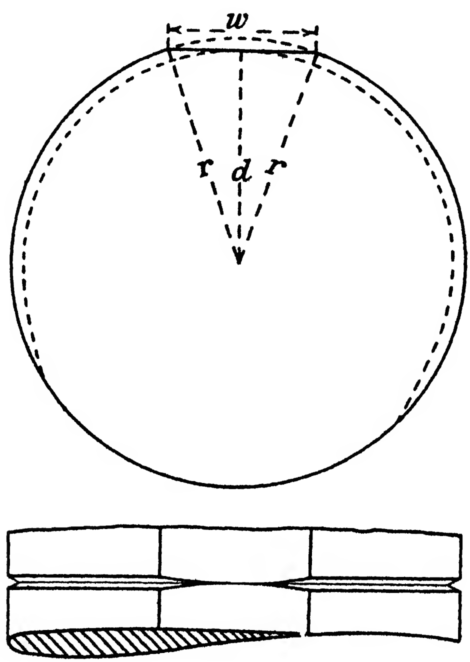


Fig. 9.

adoption of special precautions. Broaching, which may be regarded as a variation of the milling process, in which special teeth or cutters are reserved for finishing, may be relied on to produce work correct to about three ten-thousandths of an inch. That is in regard to the relative positions of the elements of the broached surface. Concentricity with external surfaces is sometimes difficult to ensure, for which reason it is sometimes advisable to finish external surfaces by location from the broached part.

CHAPTER III

MACHINABILITY

SINCE a very large proportion of components are finished by some cutting process included under the general term of machining, it is of very great importance to form a clear conception of the behaviour of materials under the action of cutting tools. There are several factors in the process, as the resistance of the metal to violent separation, the quality of the surface left by the cutting tool and the degree of approximation of the machined surface to the path of the cutting edge of the tool. All these items are generally understood to be summed up in the word "machinability." For example, a material which offered a comparatively low resistance to the separation of a chip and which was left by the tool with a smooth, untorn surface, conforming closely to the path of the finishing part of the cutting edge, would be said to possess a high degree of machinability. A material of good machinability should permit a high cutting speed without undue wear of the cutting tool. Although the final result is easily recognised it is not so easy to say upon what properties of the material machinability depends. It may be shown to vary with the composition and with the condition of a material and with sundry other factors, but it is also known to vary in a material of given composition when, so far as can be observed, there is no difference in condition. In this it is similar to other properties which are known to differ in a given quality of steel although there is no perceptible difference in micro-structure. Since so many factors affect the machinability of metals, there is much to be said in favour of assessing the ease or otherwise of machining a metal in terms of the quantity of energy required to remove a given weight of the metal in the form of cuttings. Such a number will include the effect of friction between the material and the tool face, the increase of resistance arising from work hardening, and the influence of changes in the properties of the material to be cut which follow the elevation of temperature. It must, of course, be determined for each material by a cutting test in which the power applied is measured, but it does not involve unusual

apparatus and it appears to give a reliable indication of the machining properties of the metal.

A considerable amount of research work has been done in connection with machinability during the last thirty years or so, and is still being continued. This is of very great value commercially as well as scientifically, because uniformity of machining properties in a material is essential to the successful planning of manufacture. Irregular machinability is very objectionable in a modern highly organised factory where machining times are closely estimated and plans are made for the steady flow of several streams of finished components to meet in fixed proportions at a given point where they are assembled. An unforeseen difficulty in machining some of the components may hold up all the production lines, since none can be dealt with if one series is missing. Such unforeseen and abnormal difficulty in machining may occur even though the other properties of the material are quite satisfactory. Ease of machining is of course important, but it is hardly more so than uniformity, since the planning of manufacture depends upon the estimation of times, or rather upon the repetition of estimated times. When a material is known to be difficult, allowance can be made for it, but when the degree of difficulty varies seriously we may at any time be confronted with something far beyond our allowances. Thus the whole of a manufacturing programme may be thrown out of gear and the resultant loss of time may far exceed the extra time required to machine the erratic components.

There is no great obstacle in the way of ensuring easy machinability when this is the principal factor to be considered in a material, but those materials which are pre-eminently easy to machine are usually deficient in some other properties. Some of the recent developments in alloy steels have been very troublesome, but their qualities have been so valuable that special methods of machining have had to be devised to suit them. These are discussed later in this chapter. Within recent years much progress has been made towards an understanding of cutting action in metals. For many years the range of experiment was limited to little more than the capacity of ordinary carbon tool steels, but the development of high-speed steel and, later, the introduction of the carbide tools very greatly extended the range of cutting conditions in regard to weight of cut and speed of cutting. Thus research has been stimulated and a great deal of useful work has been done.

Researches on Machinability

Several lines of inquiry have been followed, and observations have been made upon :—

1. The mode of formation of the chip, by microscopic examination of the change of structure of the material cut.

2. The stresses set up in the material and the tool, by photo-elastic methods.

3. The forces acting on the tool during chip formation under various conditions by means of specially designed dynamometers.

4. The temperatures consequent upon cutting.

5. The mechanical properties (especially the hardness) of materials cut and of tool steels at ordinary and higher temperatures.

6. The effect of mechanical work upon the properties of materials at ordinary and higher temperatures.

7. The conductivity of tool steels and alloys at various temperatures.

8. The effect of various preliminary heat treatments of the material cut.

A brief account of some of these inquiries is given below, together with references to the original papers.

The Formation of the Chip

This has been examined microscopically by Rosenhain and Sturney [1] and by E. G. Herbert [2]. In both investigations cuts were made in such a manner that it was possible to prepare and polish a section through the cut material to be cut and through the chip. The method employed by Rosenhain and Sturney is shown in Fig. 10, which shows a thin disc or collar projecting from a bar with which it is integral. Engaged with the edge of the disc is a turning tool, of the form of a parting tool but of greater width than the thickness of the disc (see plan, Fig. 10). With this arrangement it was possible to make a simple cut without interference from the material at the sides of the tool. A cut was started with this tool and, when the full depth of cut was being taken, the lathe was suddenly stopped, leaving the tool in contact. After careful removal from the lathe the disc with cutting attached was surrounded with a suitable supporting medium (electro deposit of copper), and the surface was ground, polished and etched. Enough of the disc was sectioned to show the unchanged original structure of the bar. The diagram, Fig. 11,

indicates a typical formation. There is a definitely distorted area on the top surface of the tool; a crack is formed between the chip

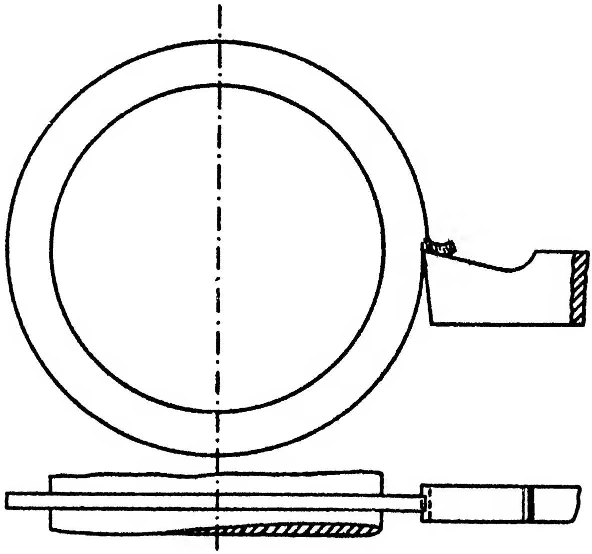


FIG. 10.

and the bar just above the edge of the tool, and there is indication of a tendency to shear at A. The shear is more or less complete

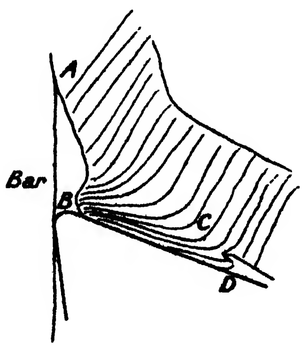


FIG. 11.

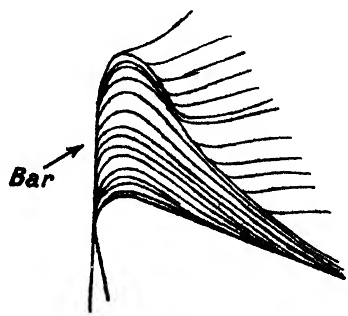


FIG. 12.

according to the conditions of cutting. It depends upon the slope or rake of the top surface of the tool, upon the thickness of the chip and upon the speed of cutting. The strength of the material in shear

as compared with its strength in other ways will also have some effect. The distribution and nature of the stresses involved will be discussed more fully in the next section. Meanwhile it is of interest to consider the metal within the zone BCD. This has been the subject of some difference of opinion, probably because it was not realised to what extent the behaviour of this metal depends upon the conditions of experiment. Take, for instance, a fairly heavy cut in mild steel with a tool having a small top rake, of not more than 20°. For a short time after the cut is started there will be a tear as shown at AB in the diagram, which proceeds in advance of the cutting edge. The material is very severely distorted by pressure on the top rake face of the tool. This material, under the influence of the heavy pressure, tends to flow, partly in the same direction as the chip away from the bar and partly into the vacant space left by the tear above the cutting edge. There is much relative motion between the different parts of the distorted material. The lower layers tend to adhere to the top face of the tool, while the upper layers still remain continuous with the chip. This is shown in the diagram of Fig. 11, which is based on microphotographs taken at a comparatively early stage. Under favourable conditions one layer after another will stick to the tool nose until what is commonly known as the built-up edge is formed, as shown in Fig. 12, which represents the normal condition during a cut. Fig. 12 is drawn to a larger scale than the previous figure. The upper layers of this built-up nose are continuously being worn away and reformed by conflicting actions. There appears to be a certain natural slope to which the chip conforms. If, by the action of wear the built-up edge falls below this, the conditions permit another layer to become attached. But if the newly attached layer projects beyond the natural form in any part the locally intense pressure very quickly wears it away.

Although the built-up edge is continually being renewed as described, it is usually more strongly attached to the tool nose than it is to the chip. It can be quite easily seen in position if a roughing tool is removed from the cut with care, and usually requires the exertion of considerable force to detach it. Each layer has been formed from the flowing chip, and the laminated structure merges into the chip gradually and without discontinuity in a manner quite compatible with the observation that the chip and the built-up nose are continuous. The metal at this point, under the combined influence of temperature and pressure, is in a plastic condition somewhat like

that of metal during extrusion processes. Intermittently, parts of the built-up edge become detached from the tool and adhere to the cut surface of the work, thus at least in part causing the irregular surface commonly associated with the conditions favourable to the formation of the built-up edge. It is quite possible for clean metal under these conditions to be separated and re-united, so that the strength and hardness of the built-up edge, referred to later, are quite consistent with the method of formation described.

The top rake angle of the built-up edge is for mild steel about 35°, which is very near to the angle which has been arrived at by experience for grinding the knife type of tools commonly used in turret lathes. When a tool is ground to this angle no permanent built-up edge is formed, but according to E. G. Herbert [2] a temporary edge is built up and worn away about 3,000 times a minute. The same investigator has found that a tool ground to a main top rake of 35° and then having a narrow flat AB about 0·4 mm. wide and 10° top rake ground just at the cutting edge, will form a permanent built-up edge (see Fig. 13). Such a tool would offer rather more resistance than a simple one to the starting of a cut, but once the edge is formed it cuts quite normally. Whether a tool with a flat as described would be more or less durable than a tool left as originally ground to 35° top rake does not appear to have been established by experiment, but the suggestion has been made that the tool with the flat might last almost indefinitely since the part subject to wear is continually renewed. The built-up edge is of very great moment from the point of view of machinability, as will be seen later when the question of hardness is considered. But it should not be thought

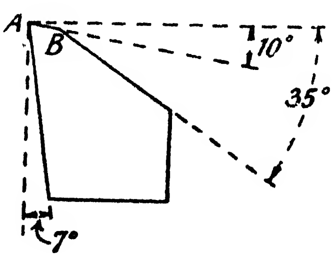


FIG. 13.

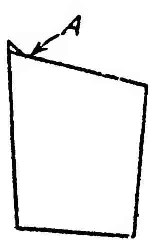


FIG. 14.

that the angle of top rake ground on the tool is immaterial because the real edge will be reformed by the action of cutting. The immediate cutting edge is so formed, but immediately behind this edge

the original tool face is exposed, as at A in Fig. 14, and if this be not in line with the natural top rake, the chip after separation from the bar will be sharply bent, thus throwing needless work on the tool and causing the generation of heat. Roughing tools ground at somewhat obtuse angles do in fact fail by the wearing of a groove just behind the cutting edge, rather than by actual blunting of the edge.

Stresses Induced by Cutting

With the aid of the photo-elastic method which he devised, E. G. Coker [8] has investigated the stress distribution in bars and tools of various kinds during cutting. The general distribution of stress as determined by this method appears to be as shown in Fig. 15. Ahead of the cutting edge and radiating from it is a system of compression stresses. Behind the cutting edge there is a system of tensile stresses also radiating from the edge. The position of the boundary between these two regions of stress is dependent on the shape of the tool, especially upon the top rake angle. When the top rake is between zero and 36° the boundary is almost in line with the top rake surface. As the top rake is increased beyond 30°, the inclination

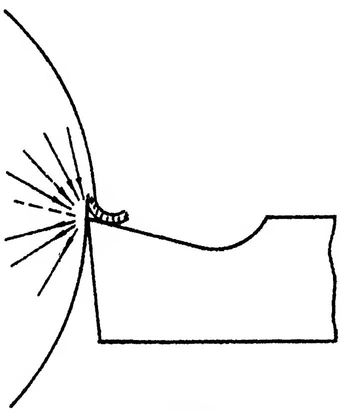


FIG. 15.

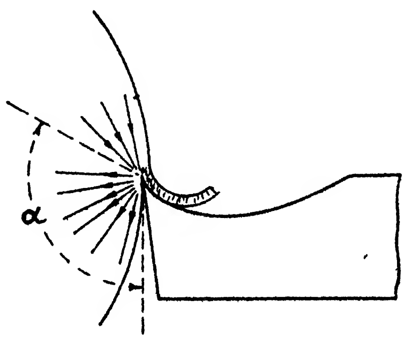


FIG. 16.

of the boundary follows much more slowly. For extreme top rake angles up to 70° the inclination of the boundary to the horizontal plane does not exceed 50°, *i.e.* a does not exceed 140° (Fig. 16). These angles were used in cutting nitro-cellulose used in the photo-elastic experiments. They could not be used on steel, but they call attention to an action which is of importance in finishing cuts. With considerable

values of top rake 40° and over, the stresses in the tension region are increased so that the material tends to be lifted by the tool and a gap a_1a_2 appears between the tool and the work if a second pass be

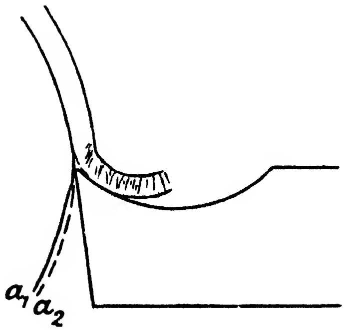


FIG. 17.

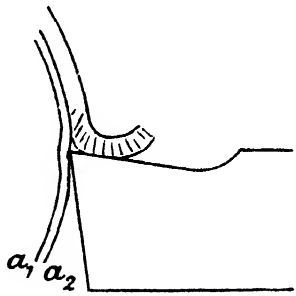


FIG. 18.

taken without additional feed (Fig. 17). If the top rake is small there is an increase of stress in the compression region and the material before the cutting edge is pushed inwards from a_2 to a_1 (Fig. 18). When this happens a second chip may be removed by another pass of the tool without feed. Figs. 17 and 18 are diagrams only, and are not drawn to scale. After comparing these results with observations made when cutting metal, Coker concludes that the ideal condition for finishing cuts coincides with the mean between the above actions, that is, that smooth, accurate surfaces are most likely to be produced when the chip is neither dragged away from the finished surface nor pushed towards it.

The Forces Acting upon a Tool when Cutting

These were shown by Stanton and Hyde [4] to vary with the top rake angle somewhat as follows. With a top rake of 40° the normal force on the top face of the tool when taking a cut on the end of a mild steel tube one-tenth of an inch in thickness at a feed of one-hundredth of an inch per revolution at 13 feet per minute was found to be about 120 pounds. The tangential force under the same conditions was 150 pounds. These values increased to 310 and 220 pounds for the normal and tangential forces respectively as the top rake was diminished to 5°. These are mean or steady values, but the instantaneous values are known to vary cyclically during steady cutting. At very low speeds, when successive shears are complete, the variations may be as much as plus or minus twenty-five per cent

of the mean value. Even at higher speeds, such as the 13 feet a minute of these experiments, the variations still exist, although they are not so great. Examination of a chip formed under usual conditions will show very clearly the intermittent crushing and shearing to which it has been subjected.

In the paper by Stanton and Hyde already referred to, the mean forces acting on the tool are resolved into forces causing indentation and forces overcoming friction, either internal friction of the material of the chip or friction between the chip and the top face of the tool. For some of the metals tested, including nickel chrome steel, nickel steel, mild steel, cast iron and normalised hydraulic tube, the tangential force is remarkably constant for the range of top rakes tested. The greatest variation is that already quoted for the mild steel bar, from 150 to 220 pounds. Hydraulic tube in the cold worked condition as received and copper showed much greater variation in tangential force on the tool. For the hydraulic tube as received the tangential force changes from 230 pounds at 30° top rake to 500 pounds at 5°. For the same range of top rake the normal force varied from 180 to 580 pounds. After being normalised the values for the same tube were tangential force 180 to 205 pounds, normal force 160 to 320 pounds. It appears that the great variation in the tangential force which was observed when the tube was in the cold worked condition is in some way due to the abnormal condition of the metal. In discussing the results Stanton and Hyde remark that " In the case of cast iron and nickel steel, in which the tangential force is independent of the cutting angle, it would appear that the shearing actions producing internal frictions were practically completed before sliding of the chip began to take place. That this should be the case would be expected for cast iron, but that it should occur for nickel steel is noteworthy."

The Temperatures Reached in the Material and the Tool during Cutting

This is a subject of growing interest, since the new cutting alloys have so greatly raised the permissible temperatures. There is some reason to hope that control of temperature may make it possible to machine, or to machine more easily, metals which have been troublesome. The tool-work thermo-couple used by E. G. Herbert has enabled temperature measurements to be made under actual cutting conditions. A cutting tool of stellite cutting a steel bar, or a high-

speed tool cutting a carbon steel bar, will give a thermo-electric effect which is quite sufficient to indicate temperatures. The particular combination used is calibrated under known conditions as a preliminary to an experiment. It is not yet possible to determine the temperatures of particular localities in the region of cutting, but the tool-work thermo-couple gives very valuable information as to the maximum temperature reached under any particular conditions.

For example, if a given cut (feed per revolution and depth of cut) be started at a low cutting speed the steady temperature near the tool edge is comparatively low, say 150° C. As the speed is raised step by step, while the other conditions remain constant, the temperature will also rise, but it will quickly reach a steady value at each speed. Similarly after each change of other conditions a steady temperature is reached, which will remain constant until the edge of the tool fails.

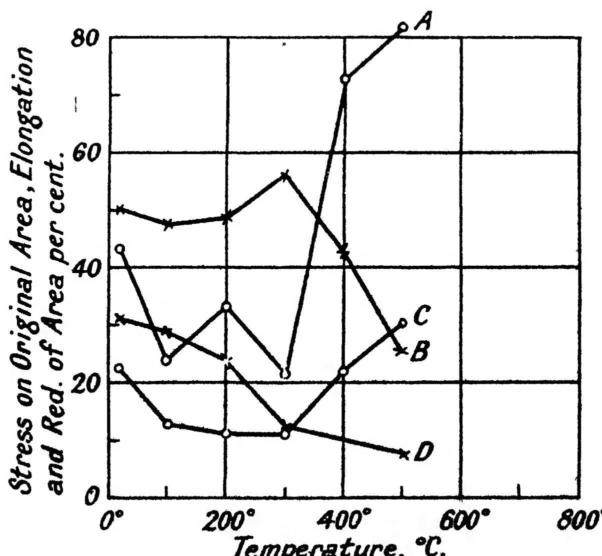
In a test on a mild steel bar with a cut 0·375 inches deep and 0·023 inches feed per revolution, a temperature of 510° C. is recorded by E. G. Herbert at 230 feet per minute cutting with water and at 82 feet per minute cutting dry. Temperatures up to 700° C. have been recorded, although it is not suggested that these actually exist at the extreme cutting edge where the tool is in contact with the cool bar. The probability is that a sharp rise of temperature occurs when the chip first begins to part from the bar. The chip may be expected to become hotter on account of the violent crushing and sliding which it undergoes, until it comes heavily into contact with the tool face and slides over it under pressures of the order of 80 to 150 tons per square inch. The already high temperature of the chip is raised still further by the frictional work of sliding on the tool face. It is not difficult to imagine the welding of successive layers to form the built-up edge under temperatures and pressures approaching those which have been recorded. The heat of the bar at the point of separation of the chip is rapidly dissipated by conduction into the body of the bar so that the temperature rise at this point is probably never so great as that ultimately reached by the chip and the face of the tool. It is quite possibly great enough to affect the machining properties of the bar, which may be influenced by temperatures of 100° to 150° C., as described in a later paragraph. For the moment enough has been written to show that the properties of the bar and the tool at room temperatures may give very little

guidance to their behaviour at higher temperatures such as may be attained during cutting.

The Effect of Temperature Changes on the Properties of Metals

To realise the effect of this temperature variation upon the action of the cutting tool, it is necessary to turn aside and consider ordinary physical tests on metals at various temperatures. Whether tensile tests or hardness tests be taken, there are available records of experiments which show remarkable changes in properties as temperature is altered. The tensile strength of some steels varies both up and down as tests are made at increasing temperatures. Ultimately, of course, the strength steadily falls, but before the final descent there are fluctuations. Fig. 19, for example, shows a record of tests made by F. C. Lea on a steel of the composition given below [6]. Although differing in detail for steels of various compositions, the changes shown are typical of the behaviour of a wide range of steels. Carbon =0·65 per cent. Manganese=0·80 per cent.

It is reasonable to suppose that if this steel could be maintained



A = Reduction of Area. C = Elongation.
B = Ultimate Stress. D = Limit of Proportionality.

Fig. 19.

during turning at a temperature of about 100° C. corresponding to a point on the curve B, where tensile strength has a minimum value, it would be cut with least power and possibly with least disturbance of the adjacent metal. Exact correlation of such points as this with corresponding points in a cutting test is difficult if not impossible. It would require the measurement of temperature instantaneously at definite points in the bar and the chip, so that the effective temperature at the moment of rupture could be known. Although direct comparison with test results in this way would be difficult, it is possible to get some indirect confirmation of the hypothesis. Cutting tests made by E. G. Herbert have shown a remarkable fluctuation of durability with change of speed when taking comparatively light cuts. With heavier cuts the durability diminishes steadily as the speed rises, and this is the most widely known relationship.

The waves in the speed-durability curve in the lower part of the speed range are probably due to the interaction of temperature effects on the tool and the work. These effects are not identical for different steels, *e.g.* for high-speed steel and ordinary carbon steel. It is possible also that the temperature of the wearing face of the tool is not equal to that at the point where the chip is being separated from the bar at any given instant. The two points are separated by an appreciable distance even for quite small cuts, and the motion of the parts prevents equalisation by conduction. E. G. Herbert has demonstrated that temperature has an influence on cutting action by taking similar cuts in his tool-testing machine with the tool and work immersed in baths of various temperatures. The form of the durability curve is the same for each temperature, but the curve moves bodily to the left or right as the temperature of the bath is raised or lowered. Similar results were obtained by taking a series of tests with light cuts and comparing them with a series of heavier cuts. The curves were generally similar, but one was displaced relatively to the other in a way which would correspond to the higher temperature occasioned by the heavier chip.

Various experimenters have observed that when light cuts are taken, of the kind used in finishing, the quality of the surface changes with increasing speed. Within a certain range of speeds, which depends upon the material, it is possible to produce a good finish. Outside this range, above and below, the finish is unsatisfactory for a period, but other ranges may be found within which a good finish will again be produced. In the earlier experiments in this direction

the range of speeds was somewhat limited because at that time the quality of finish produced by high-speed tools was not very good at any speed, and carbon steel tools permitted only a very limited range of speeds. In consequence of this limitation of speed it was thought that beyond comparatively low speeds a good finish could not be produced by cutting tools, although higher speeds could be used for roughing cuts. The Whitaker ring referred to by E. G. Herbert is a bright circular band which appears when a surfacing cut is taken across a mild steel disc running at a constant number of revolutions per minute. As the tool is gradually fed from the centre outwards, the surface will appear rough until a certain diameter (and cutting speed) is reached. Then for several revolutions the cut surface will be smooth and bright. Afterwards, at still larger diameter, it will become rough again. It might be thought that the change was a consequence of some variation in the quality of the metal of the disc, but it has been found that in subsequent cuts across the surface the ring may be displaced inwards or outwards as the speed of revolution is raised or lowered. The introduction of the carbide tool has greatly widened the field of experiment, and it now appears that satisfactory finish may be produced at speeds far beyond those previously thought. Starting at a low speed, say 15 feet per minute, and gradually raising it until a speed of 300 or 400 feet a minute is reached, it is interesting to examine the surface of the bar and to compare the finish produced at the various speeds. Up to 100 feet per minute the surface is poor, being grey and rough. Above that speed bright bands begin to appear round the cut surface, increasing in width and frequency as the speed is raised towards 250 feet per minute, when they become continuous over the whole surface. As the speed is raised still higher the quality of the finish continues to improve up to the highest speeds so far attainable. The figures just given refer to one quality of steel and may be subject to modification for other qualities, but they illustrate a tendency which appears to be common to all. At all the speeds quoted above, the cutting was done without cutting liquid. No reference is made to the usual finishing cuts with lubricant at speeds below 50 feet per minute.

Although it is likely that the fundamental factor is the temperature, it is not certain how the effect is produced. It may be attributed to several causes. There is the built-up edge discussed above, whose formation and maintenance probably depends partly upon the working temperature. There is also the effect of the working

temperature on the physical properties of the test bar, making it more or less easy to cut. To some extent, but probably a small one with carbide tools, the condition of the cutting edge may vary with its temperature.

When a cutting test is made at increasing speed as described above, it is of interest to observe that the formation of the chip is very different at low speeds from that at high speeds. At speeds up to 8 feet per minute the cutting leaves the tool in separate small sections. As the speed rises the chip becomes continuous on the side which rubs on the tool face, but remains for a while deeply indented on the other side (the inner side of the curve). At moderate speeds the chip is curved sharply, but as the speed rises the curvature becomes less until at high speed the chip is almost straight as it flows off the tool. Whether this is purely a speed effect owing to the lack of time for deformation of the chip to take place, or whether it should be attributed to the changed resistance of the material at high temperature, is not known. Both causes may be at work.

In the discussion of cutting phenomena above, the examples have mainly been taken from experiments on carbon steels as the material cut. Many of the points made are even more applicable to some of the alloy and special steels, which are more difficult to cut. These and other effects are considered below.

Work Hardening Effects in Cutting Metals

A great deal of very interesting work on the variation of hardness of tool steels as the temperature rises has been done by several experimenters. But even more interesting is the study of the hardness of different parts of a test bar and chip during a cutting test. This work was initiated and carried on by E. G. Herbert, who has done much to elucidate the behaviour of the alloy steels under the action of cutting tools. Generally his method of experiment is to stop a machine suddenly in the middle of a cut and to remove the bar with the chip attached. The part of the bar adjacent to the chip and the chip itself are tested for hardness. The built-up edge which sometimes remains attached to the tool nose has also been examined. Remarkable variations in hardness have been detected in this way. In some materials the hardness of the chip and the bar near the newly cut surface are much greater than the original hardness. The change is particularly noticeable in some of the alloy steels,

many of which are austenitic and thus very susceptible to work hardening.

The figures which follow were obtained by E. G. Herbert with the aid of his pendulum hardness tester. They have been converted to equivalent Brinell Numbers. In an ordinary mild steel of original hardness 163 the hardness in the path of the tool became about 300, the chip attained a hardness of about 330, and the built-up edge a hardness of 448. Corresponding figures for a stainless steel were 142, 430, 360 and 534. The hardness of the built-up edge is astonishingly high in comparison with that of the original bar.

The following suggestions derived from practice in the machining of stainless and heat-resisting steels are in general agreement with the results considered above. With these steels it has been found that the application of pressure, as when a tool rubs without cutting, will render the surface almost uncutable. If by accident a surface has been compressed it may be necessary to soften it, or, more conveniently, to start a cut in such a way that the hardened surface need not be pierced. If a new start can be made in such a way that the cutting edge gets behind the hardened surface it is usually possible to remove the hardened spot and to continue cutting. To obviate any likelihood of work hardening the surface by pressure without cutting, tools should be carefully ground with slightly greater clearance than is used for mild steel and with more top rake. The limit to increasing top rake lies in the weakening of the tool which ensues. After a time this overtakes the reduction of cutting force. Very great care is necessary to ensure that the cutting edge is really sharp and that the unavoidable rounding where the top face and clearance surface of the tool meet is of as small a radius as possible. Fig. 20 shows a tool with suitable angles for stainless steel. Ordinary cutting fluids, as for mild steel, are suitable for most operations on stainless steel, but tallow is good for screw cutting. Turpentine is useful when drilling small holes, and the points of drills should be ground thin to reduce to a minimum the inefficient rubbing action of the unfavourable part of the drill edge.

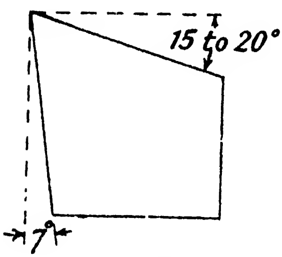


FIG. 20.

Free Cutting Steels

These result from the presence of a relatively high percentage of sulphur and phosphorus. The latter goes into solid solution and produces a general embrittlement, which is objectionable. If phosphorus be kept down and the sulphur be kept fairly high a steel may be produced which is free cutting without being so seriously embrittled. It is necessary that the percentage of manganese should be high enough to combine with all the sulphur in the form of manganese sulphide. This will exist in the steel as an inclusion, and in rolled bars it will lie in streaks in the direction of rolling so that the longitudinal continuity of the other constituents will not be impaired. A steel of this kind will give a fairly good impact test when the blow is struck at right angles to the direction of rolling, although it will not be quite so good if the specimen be cut in the other direction. For many components the weakness in one direction will not be at all objectionable. In such cases suitable design will enable satisfactory working properties to be combined with easy machinability.

Difficulty is sometimes found in machining annealed steel. The material is not hard to cut but is apt to tear, and the surface is likely to be rough. Steel in the normalised condition is easier to machine and cuts cleanly, leaving a smooth surface.

The presence of even minute quantities of lubricant on the surface to be cut has a remarkable effect on the cutting action. Coker records that a thin mild steel plate, cut without any lubricant, shows a region of overstressed material which extends below the path of the tool produced. Even a trace of lubricant alters the shape of this overstressed region, and it lies entirely outside the produced path of the tool. This implies that in the first case the machined surface will lie on material which has been permanently distorted. In the second case the machined surface will lie on material which has not been permanently strained. The value of lubricant in the production of well-finished surfaces is well known. It is possible that it may be associated with the freedom from overstress mentioned by Coker.

CHAPTER IV

SETTING OUT

Except when work which is to be machined is of very simple shape, which may be developed directly by means of the slide rests of machine tools, it is usual to mark it out so that the edges of finished surfaces are indicated by scribed lines. These lines serve as guides in setting the work up in the machines, and they define the limits of feed for the cutting tools. In passing, it may be mentioned that when many similar parts are to be machined the labour of marking out each one individually is saved by using a jig or fixture. The marking out is then done once for all in making the jig and is not repeated on each piece of work. The use of jigs and fixtures is described in Chapter VI.

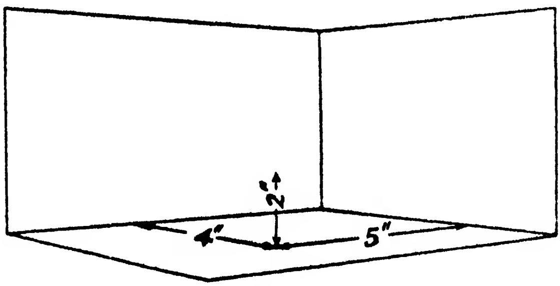


Fig. 21.

The method of marking out and the principles on which it depends are the same whether applied to a single piece of work or to a fixture which may be used on many pieces of work. The object in view is to mark on a rough casting or forging certain lines and points which will indicate the positions of finished surfaces or the axes of bored holes. Three planes of reference are used in order to determine the required positions in space. They may be likened to the bottom, one side and one end of a box, as shown in Fig. 21. From these planes the position of a particular point may be found by measuring, say 2 inches upwards from the base, 4 inches forwards from the back and 5 inches to the left from the end. Suppose, for example,

that the bracket shown in the three views of Fig. 22 is to be set out. For the moment it exists as a casting, and the purpose for which it is

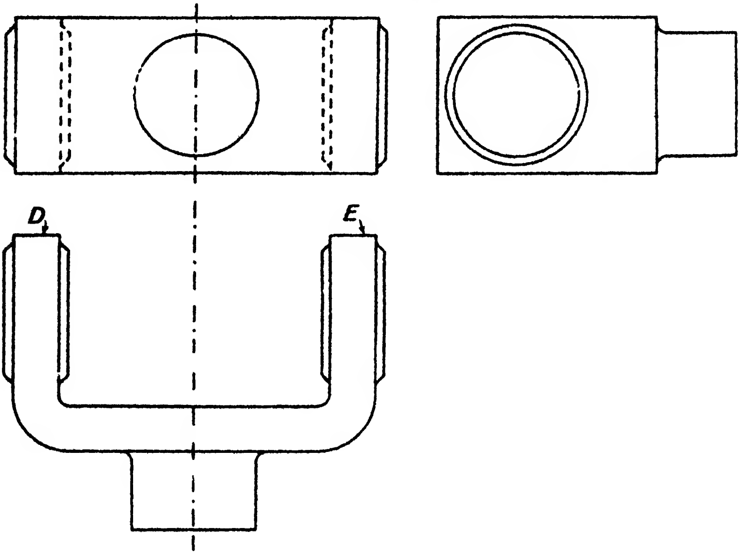


Fig. 22.

intended does not entail that any of the outer surfaces, except the faces of the bosses and the ends D and E, shall be machined. The faces of the bosses should, however, be approximately square with

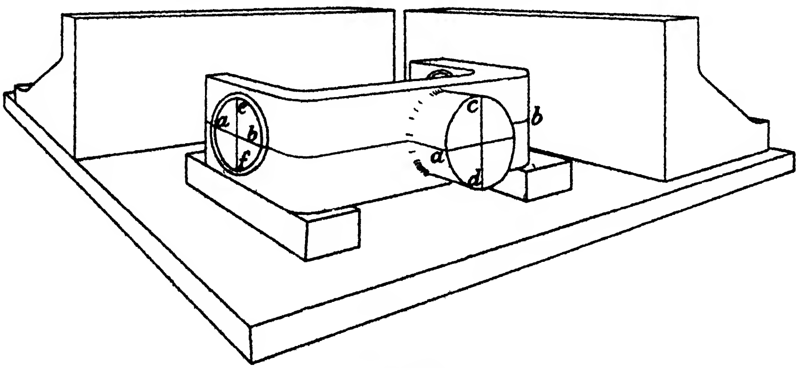


Fig. 23.

the holes. The block is set up on distance pieces of known height, say ½ inch, as shown in Fig. 23, the underside being parallel to the base plane and two other sides parallel to the side and end planes. In each case

the distance from the work to the adjacent plane is known. It may be made equal to some convenient number, so that it may easily be added to the dimensions given on the drawing. Let it be placed as shown in the figure. Then, if the centre of the hole is to be $1\frac{1}{4}$ inches from the lower face of the block, the scriber point is set to $1\frac{1}{4}$ inches plus $\frac{1}{2}$ inch from the base plane and a horizontal line *ab* is drawn. Next the scriber is set to the required dimension, and working from the end plane the short vertical line *cd* is drawn. The intersection of the two lines *ab* and *cd* indicates the point where the axis of the required hole meets the side of the casting. It should be centre dotted and a circle slightly larger than the hole should be marked round it, in order to serve as a guide when the hole is drilled. Unless the hole is very small, say less than $\frac{3}{8}$ inch in diameter, a few smaller concentric circles will assist in setting the drill to run concentrically with the given axis. A repetition of the process will

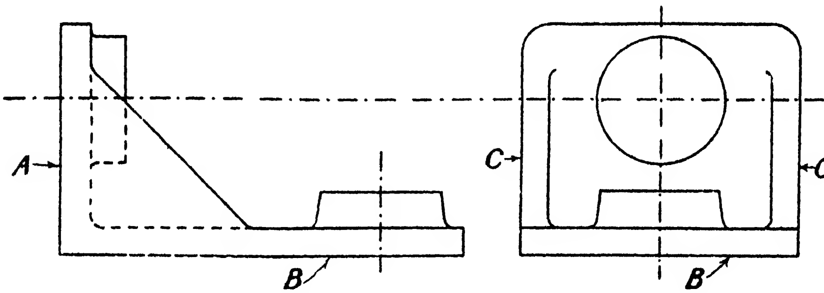


FIG. 24.

indicate the positions of the other centres shown on the drawing (see Fig. 23 again).

If there should be one or more of the outer surfaces to be machined as at A, B and C, Fig. 24, it may be well to plane them before marking out the centres of the holes. But if the outer machined faces are only partial, as in D and E, Fig. 22, they may be marked out when the centres of the holes are done. As an aid to setting the block correctly on the machine, lines may be scribed right round as shown in the figures. The similarity between the three views given in the drawing and the marked faces of the casting will be easily traced in the foregoing explanation, if allowance be made for the distance between the block and the planes when comparing dimensions. The drawing is, in fact, made with the three reference planes in mind, but they are folded down into the single flat sheet for convenience.

When the pattern-maker or wood-worker sets out his work he has the same reference planes in mind, but as a rule he prepares two sides of the wood as flat surfaces perpendicular to each other. On these he sets out the forms shown in the drawing. The third perpendicular plane is not usually formed on the wood, but is represented by lines scribed round the piece on the other planes. These lines serve as a base from which longitudinal measurements are taken. When using wood the plan of forming the necessary reference planes on the material itself is satisfactory and convenient because wood is easily worked. Also it is usually supplied in rectangular blocks. But metal parts are usually supplied as castings or forgings closely resembling the final shape, and the cost of finishing the necessary planes on this work is more serious.

Also the surfaces available would not be extensive enough to form accurate bases for measurement. The expense of preparing plane

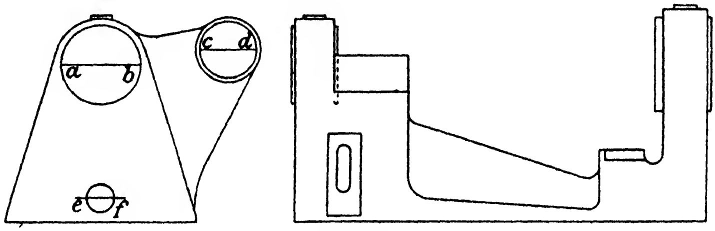


FIG. 25.

surfaces on the work for setting out is therefore avoided by using surfaces external to the work. For example, if a marking-out table or other plane surface be available, the rough work (casting or forging) may be supported upon it by means of distance blocks, etc., so that certain centre lines are parallel to the table, as in Fig. 25, *ab*, *cd* and *ef*. In this position lines may be scribed on the work at constant distance from the table and at any height above the surface, according to the setting of the surface gauge used. For distances measured at right angles to these original ones, the work may be turned so that the original lines are perpendicular to the table, when the lines *gh*, etc., required may be scribed parallel to the surface of the table (Fig. 26). Finally a third set of lines may be scribed if required after turning the piece to a third position perpendicular to both the others. Although the method of marking out from a single surface, by turning the work into different positions as described, is the one most used, it is possible to mark out from three perpendicular planes, although

two of these are usually incomplete. For this purpose the marking-out table must be supplemented by angle plates or squares. The work then need not be re-set, but it must be set initially in correct position with regard to all the planes (see Fig. 23).

Whether the simple table or the table with angle plates or some similar device be used, the process of marking out from external planes is usually much less expensive than it would be if the reference planes were actually machined on the work. It is also more accurate on account of the larger surfaces which can be used, since the piece

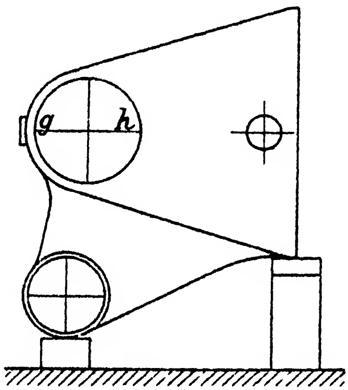


Fig. 26.

is held on the marking-out table by its own weight or by clamps, and so the table becomes an extension of the work.

When a special marking-out plate is not available, a machine table may be used provided it is in fairly good condition and is not bruised to such an extent as to interfere with the free and accurate movement of the surface gauge.

Machining to a Marked-out Line

Considering the resultant accuracy possible when machining to a marked out line, there are three items which affect the result. First, how near to a specified dimension may the scriber point be set. Second, what is the width of the line drawn. Third, how closely can a cutting tool be made to follow the marked line.

Types of Surface Gauge

The answer to the first of these questions depends upon the kind of gauge used. If the point is set to the required height by means

of a scale, the result should be rather less than one-hundredth of an inch in error, but that is about all that can be relied upon. A lens will reduce the error to about one-half or one-third of a hundredth of an inch. For settings closer than, say, three or four-thousandths of an inch, it is better to use a gauge with a graduated stem in conjunction with a vernier on the sliding part (see Fig. 27). With this, settings as near as a thousandth of an inch are possible. As an

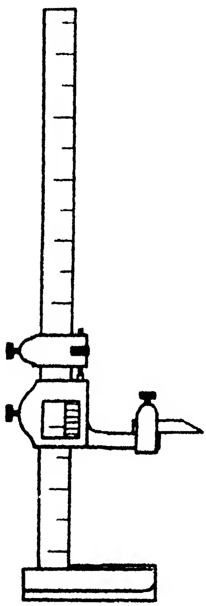


Fig. 27.

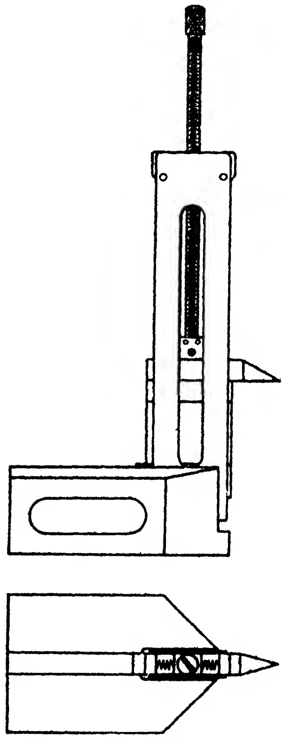


Fig. 28.

alternative a micrometer type of surface gauge may be used. It is much easier to read and will give greater accuracy than the vernier pattern.

When even closer settings are needed the surface gauge made to take precision end blocks, of the Johansson pattern, is valuable. This will enable lines to be drawn in positions known to one ten-thousandth of an inch. The device is illustrated in Fig. 28. At the top of the base-block there is a carefully finished plane at a known distance

from the base. This plane is parallel to the base and is used as a wringing surface to which piles of one or more gauges can be attached. On the uppermost of these gauges the special scriber piece is wrung. Thus, by using piles of gauges of suitable heights relative displacements of the scriber point known to one ten-thousandth of an inch are obtainable. Although the spacing from line to line may be known to this amount, it is not so easy to be sure of the distance of a line from the base. This distance depends upon the way the scriber is sharpened. If the lower face is flat and all sharpening is done on the upper face, as in Fig. 29a, the position of the line drawn will differ but little from the height of the gauge base plus the thickness of the gauge blocks used. With this arrangement it is possible to draw a line within one or two ten-thousandths of an inch of a specified position. The difficulty of obtaining results of this precision from the marking out when the lines are to be used as guides in

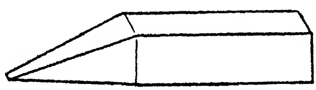


Fig. 29a.

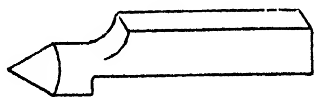


Fig. 29b.

machining lies in the fact that a line to be visible with the unaided eye must be about two-thousandths of an inch in width. Unless the line is drawn on a carefully prepared surface it will not easily be seen unless it is two or three times that width. It is therefore necessary to adopt some means whereby some particular part of the line, such as the upper or lower edge or the centre, may be used.

Observation of Marked-out Lines

A microscope with suitable cross-lines will enable this to be done when the line is used for setting work up in a machine. This is described on p. 84. Although a line may be drawn so that the position of its lower edge is known to within a few ten-thousandths of an inch, and although it may be used with the aid of a microscope for setting the work precisely, it is not suitable for checking the position of the edge of the finished surface to this degree of accuracy. The corners of the machined face are not definite enough for this. It is therefore better to take direct measurements from some datum surface to check the depth of the final cuts. Often a micrometer may be used for the purpose, or, as an alternative, a surface gauge

with indicator to compare the height of the machined face with a gauge block or blocks. Figs. 30 and 31 respectively show how the

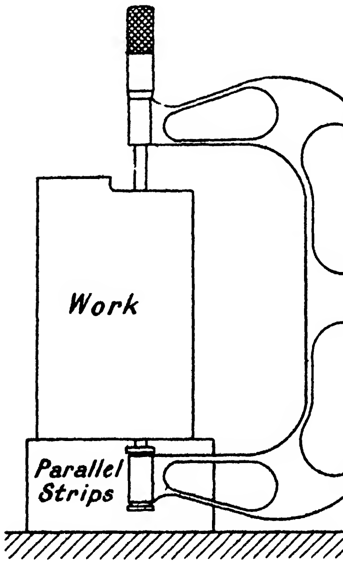


FIG. 30.

two methods are applied. For small movements the micrometer feeds of a machine may usually be relied upon, although they are not

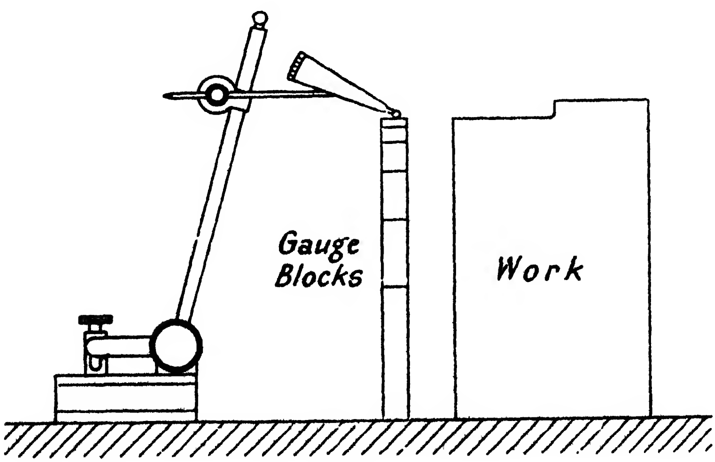


FIG. 31.

always correct for longer distances. When a cut has been taken over a surface in a milling machine for instance, and the surface gauge shows a certain amount to be removed, the micrometer feed may be used with some confidence to set the cutter for the final cut.

It is sometimes desirable to use the microscope by setting it to an edge, or rather to a surface, since the edge of machined work is usually rounded. For this purpose a small square, as shown in Fig. 32, is convenient and accurate. The face A is carefully finished square with the inner face B which rests on the surface to be located. Across face A a fine line, CD, is drawn so that it lies exactly in the continuation of the plane B. Location then depends upon the part of the work which is not affected by the broken edges.

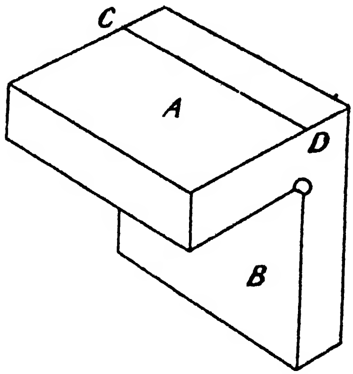


FIG. 32.

Devices for Marking Centres

When scribed lines are used to indicate centres for boring, the

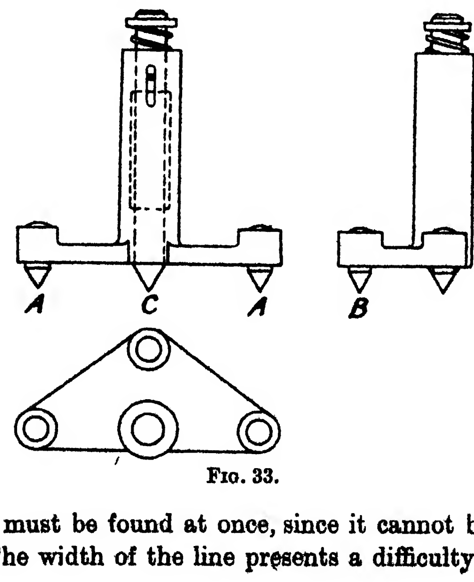


FIG. 33.

right position must be found at once, since it cannot be corrected by trial later. The width of the line presents a difficulty, but there are

several ways in which it may be overcome. One way is to use the lines drawn perpendicularly to each other to locate a special centre punch at their intersection. The punch is shown in Fig. 33. The auxiliary points AA are placed in one line and the punch is moved along that line until the third point B drops into the transverse line. The centre punch is then situated directly over the intersection and may be lightly tapped. This device will give much better results than can be obtained with a simple punch placed by eye only.

An appliance which will enable centre dots to be placed in position without the aid of scribed lines is shown in Fig. 34. The body is

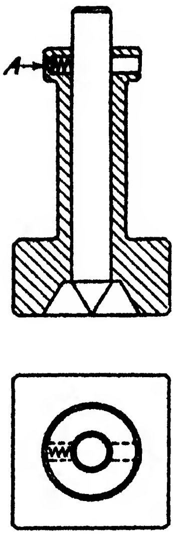


Fig. 34.

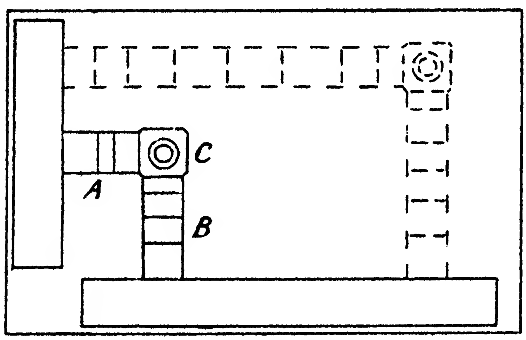


Fig. 35.

made of hardened tool steel, the centre hole being lapped to fit the hardened punch. After finishing the bore, the block is mounted on a mandrel and the four sides and the base are ground carefully to suitable dimensions, so that they are true with the bore. Fig. 35 shows how the punch is used in conjunction with distance blocks and straight edges or a special square to place dots as required. With care this method should be little less accurate than the button method. The spring A (Fig. 34) retains the punch in place.

The square illustrated in Fig. 36 is very useful in conjunction with the centre punch block just described. The thickness may conveniently be equal to the ordinary Johansson pattern blocks. Although

not essential, a definite width of blade, such as 1 inch, will save trouble and reduce the risk of error if marks are dimensioned from two edges of a plate.

The centre dot marked by one of the methods described above is then used to support one end of the centre bar with spring plunger shown in Fig. 72, p. 83. The other end is placed on the dead centre of the lathe to be used for boring the hole, so that a sensitive indicator in contact with the bar will show when the centre dot is concentric

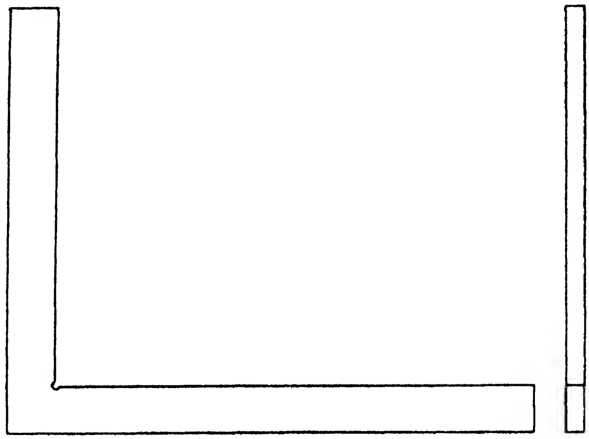


FIG. 36.

with the lathe axis. Very good work can be done in this way, but it is advisable to use a symmetrically sharpened scriber point, so that the punch will be guided over the centre of the line without regard to the depth of the mark. Figs. 37 and 38 show the effect

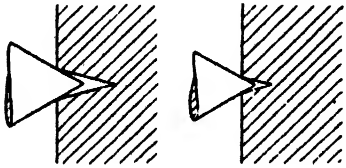


FIG. 37.

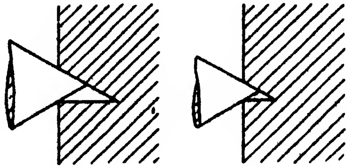


FIG. 38.

of different depths of line with two differently sharpened scribers. The form shown in Fig. 37 gives the same location to the centre punch irrespective of the pressure used in scribing.

There is an objection to the symmetrical vee when the distance from a line to a given edge must be exactly known. This is most easily determined when the scriber is bevelled on one side only as described on p. 52. But when the necessary dimension is that from bored holes to the edge of a plate or similar piece of work, it is usually more convenient to bore the holes correctly placed in relation to each other and approximately at the specified distances from the edge. By leaving these dimensions a little plus, the edge may be finished finally by measurement from plugs fitted in the bored holes (see Fig. 39). This method of selecting the more convenient surface

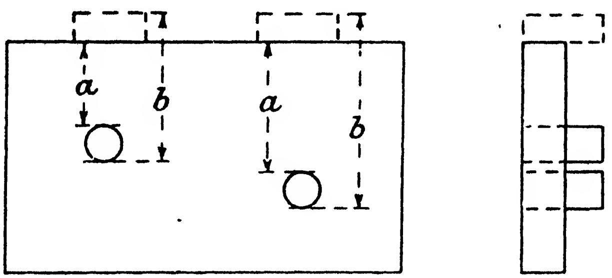


FIG. 39.

to be adjusted in the last operation will often be found to simplify difficult operations. Dimension lines *a* and *b* show alternative methods of measurement.

Preparation of Surfaces for Marking Out

Since the width of the marking lines is very important in exact work, it is worth while to consider what widths are usually employed. On a smooth steel surface covered with a layer of copper by means of a copper sulphate solution a line of about one or two-thousandths of an inch may be seen in a favourable light without the aid of a lens. But this preparation, although it is commonly used for marked surfaces, is not perfect for lines to be viewed through a microscope. The film of copper tears off irregularly and leaves a ragged edge, very indefinite when magnified.

Treatment with the following solution is recommended by Mr. Gregory of the University of Sheffield. It gives a dark, almost black, blue-grey surface which contrasts very well with the bright steel of a scratch or scriber mark. The coating is strongly adherent

and does not show a ragged edge even when viewed by means of a microscope.

Selenious acid	20 grams.
Copper sulphate crystals . .	10 grams.
Concentrated nitric acid . .	15 c.c.
Water	80 c.c.

The solution is fairly strongly acid, and the surface should be washed with water after application.

Widths of Marking Lines

The markings on metal scales in ordinary use vary from two to six-thousandths of an inch. Very much finer lines than these can be drawn on steel by means of diamond points which will endure without appreciable wear for a long time. Lines from one ten-thousandth of an inch in width downwards may be drawn in dividing machines with the aid of such diamond points. The wider of these are used for the scales of measuring machines, when they are observed by means of a microscope. They are hardly visible otherwise. Very fine lines are drawn for diffraction gratings, as many as twenty thousand to the inch, but these are not of great interest in machine work, except as showing what is possible in fine dividing and marking. Uniformity of thickness in fine graduating is obtained by applying a constant load to the marking point, not by attempting to guide the point at a fixed depth relative to the surface to be marked. A convenient device for the purpose is shown on p. 154, Fig. 126. This is adaptable to lathe, milling machine or other machine used for graduating.

Provided certain precautions are taken, it is possible to work with a marking line to a tolerance less than the width of the line. One method employing a special centre punch has been mentioned above. A microscope may also be used for the purpose of setting up from a marking line. The microscope must be fitted with cross-webs. The magnification need not be high, say from ten to twenty diameters, but some precaution must be adopted to ensure that the same part of each line is taken in the observations and settings, *i.e.* that the cross-web is always set at the same distance from the edges of the marking lines. A lightly scribed line with an ordinarily sharp point is about two-thousandths of an inch wide. At fifteen diameters such a line will appear to be three-hundredths of an inch wide. It is

likely that both this line and the cross-web will run right across the field of view, so that if they are parallel the cross-web may lie anywhere between just touching the mark at one side and the same position at the other side. There may be a variation of more than one-thousandth of an inch between the two positions; which is too great for the class of work under discussion. It is assumed above that the cross-web is indistinguishable from the mark. Fortunately this does not usually happen. The cross-web is not so highly magnified as the marking line, since it is viewed through the eyepiece only. It appears therefore to be much narrower than the scribed marking line and, owing to its different surface quality, it can usually be picked out from the wider scribed line clearly enough for it to be set centrally.

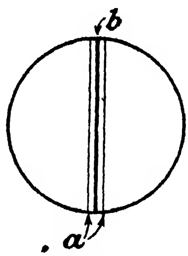


FIG. 40.

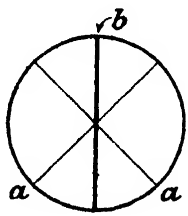


FIG. 41.

Thus a setting correct to two ten-thousandths of an inch may be attained.

If the microscope should have double cross-webs set a little distance apart, shown at *a* in Fig. 40, the marking line *b* may be set midway between them with very great precision. When the parts are close together, as in Fig. 40, the eye is able to detect amazingly small departures from equality. More often the cross-webs are single, being set at right angles or arranged to permit of being set at any angle. They may then be used as shown at *aa* in Fig. 41, which also permits of great accuracy of setting over the marking line *b*.

A microscope may be carried in a suitable mount from the tool post of a lathe with its axis horizontal. The mount should preferably have some vertical adjustment. For horizontal adjustment the slide rest can be used. Applications of the microscope to the setting of work are referred to in Chapter V.

In fine work the direction of illumination is important when observing a line since the apparent position of a scratch viewed through a microscope depends on whether the scratch is lighted

centrally or from one side. In the latter case one side or the other may be lighted and the line will appear to move by half its width

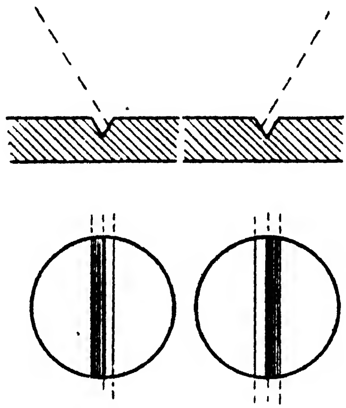


Fig. 42.

as the light is moved from one side to the other. This is illustrated in Fig. 42.

Sine Bar for Setting Out Angular Outlines

For marking out complex outlines on plane surfaces the device shown in Fig. 43 is very useful. It is essentially a combination of

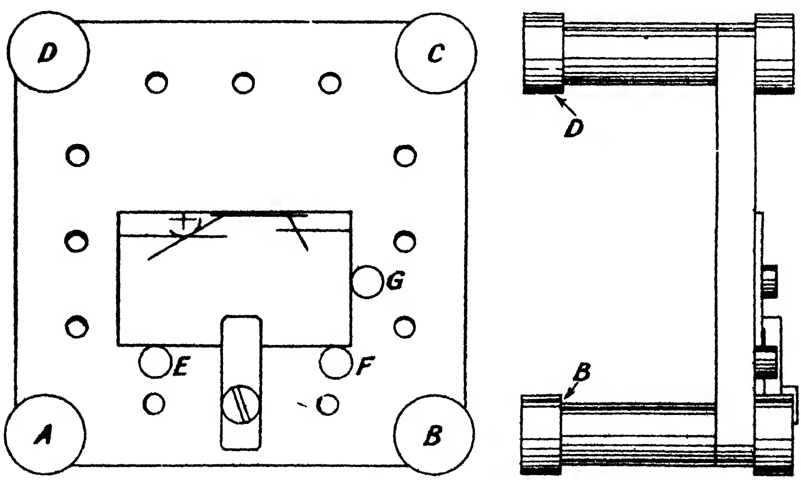


Fig. 43.

angle plate and sine bar, which are generally used together for setting out, since some means of supporting the work vertically above the

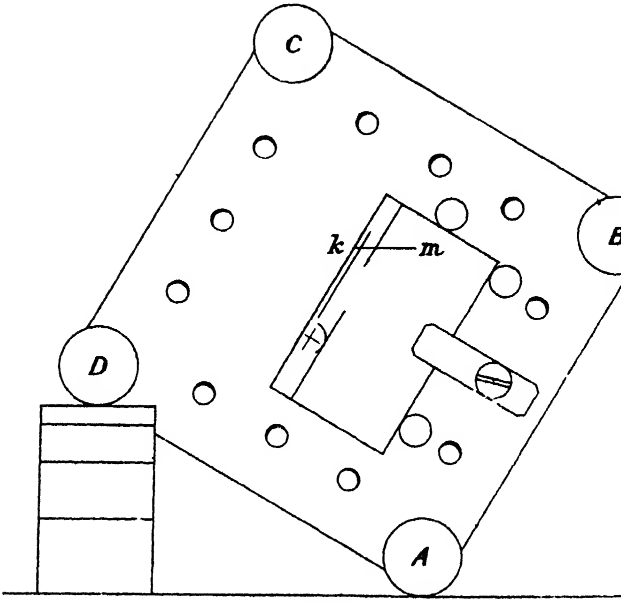


FIG. 44.

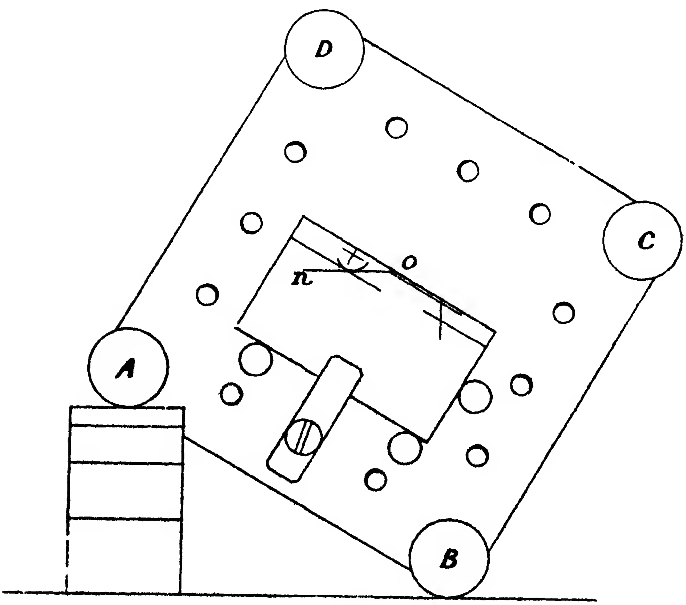


FIG. 45.

surface plate is usually needed. The arrangement shown in Fig. 43 is complete in one piece, and is correspondingly easy to handle. It consists of a square plate of convenient size for the work to be done; 7 and 12 inches square are suitable sizes. At the corners are inserted cylindrical buttons A, B, C and D, at either 5 or 10 inches centre distance. The angle between the centre lines is a right angle. The plugs A, B and D are extended at the back of the plate to act as supports and so to avoid the use of a separate angle plate. The plate is provided with a number of tapped holes so that work such as gauges or templates may be fastened to it by clamps. The advantage of the four buttons on the face of the plate is that either A and B or

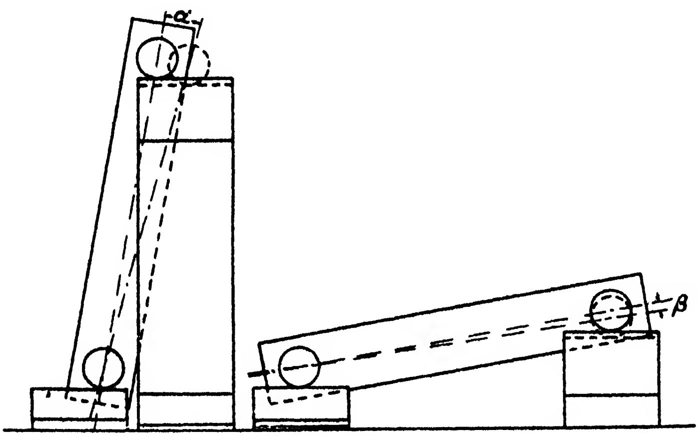


FIG. 46.

B and C may be used, so that lines at an angle of more than 45° to either of the sides AB or BC may be drawn from the other side, as shown in Figs. 44 and 45. In this way the use of the sine bar for angles approaching 90° is avoided, since the complementary angle may always be used. Owing to the rapid change in the angle for small changes in the sine when the angle is nearly 90°, the sine bar is very much affected by slight errors in the size of the setting blocks in this range. The effect is shown in Fig. 46, which shows the alteration in the angle for the same alteration in the height of the blocks at 10° and at 80°, compare β with α. The advantage of working in the lower range is obvious.

Figs. 44 and 45 show how the sine plate, as it may be called, is used in setting out a complex outline as marking the lines *km* and *no*.

When used in conjunction with a scribing block of the Johansson pattern very precise work is possible, both in the spacing and the direction of the lines.

Use of Indicator to Check Work on Sine Plate

As the work is clamped to a plate larger than itself and is not released until completely set out, accuracy is improved by reason of the use of comparatively long base lines. When the piece has been cut out to the lines it may be checked by reclamping it to the plate and tracing out the outline, while the sine plate is set up in the successive positions as before, with a sensitive indicator on the scribing gauge in place of the pointer. The indicator will show any deviations from the required form. Care is needed to replace the piece correctly on the plate. The longest straight side should be used to give the direction and some edge nearly at right angles to find the position along the first line. Very often two edges of the piece are not required for the gauge outline. When this happens these two edges may be rested against the plugs E, F and G, Fig. 43, when first setting up, and the same plugs enable the original position to be easily found when replacing the gauge to check it.

The use of an indicator and gauge blocks for checking an outline in this way avoids the uncertainty due to a rounded edge, because the readings can be taken with the indicator in contact with the part of the surface away from the corner. The rounded edge is always liable to cause trouble when an outline is to be followed closely by a cutting tool, but there will be least trouble if the tool can be arranged to enter the work at the marked side. There will then be but little tendency to break the corner away and so to spoil the mark. The draw-cut shaping machine is an improvement on the ordinary type for this reason. The slotting machine also is very good for enabling a line to be seen on the top surface of the work at which the tool begins to cut. Even on work of medium accuracy the less the edge is broken the better. so the point is worthy of consideration in selecting a machine.

CHAPTER V

DEVICES USED FOR SETTING WORK IN POSITION FOR MACHINING

THE first setting of a casting or forging in a machine does not as a rule involve very close work. It is necessary to be sure that all machined surfaces will clean up and that the thickness of metal left shall be fairly uniform, but settings to about one thirty-second of an inch are usually near enough. These do not call for any special methods or devices. But a great many jobs cannot be completely finished in one machine. Other jobs might be completed in one machine with the aid of special fixtures, but these may not be available.

Thus for various reasons it happens that a great deal of work must be reset after partial machining. Such resetting varies from the simple changing of a partly turned piece from one lathe to another, or even end-to-end in the same lathe, up to complicated resetting of a piece in some specified angular position on a milling or planing machine table. The first-mentioned operation is so commonplace that little description is needed, although its very simplicity may induce carelessness. For example, if the ends of a centred workpiece have not been squared, any change in the angle of the lathe centres will give a different bearing in the work, and the later turning will not be true with the first. The effect is shown in Fig. 47, where the displacement a is due to change of centre angle. Provided the centres in the work are well formed and the ends squared, small differences in the angles of the lathe centres should not matter. But as a precaution, to minimise the effects of possible carelessness, some

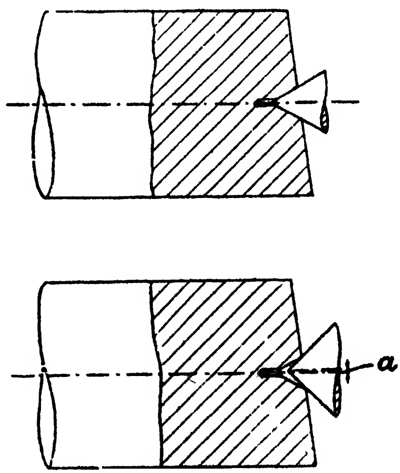


FIG. 47.

mechanics drill centre holes and countersinks as small as may be, having due regard to the weight of the piece. It may be remarked that the general tendency is to make centres larger than is really necessary, which perhaps accounts for the much too common practice of removing the centres after the work is finished. A centre of suitable proportions may be quite small and need not cause any disfigurement, and it is a great advantage to have it left if the work should return to the shop for alteration or repair.

The dimensions of suitable centres to be drilled for lathe work are given in the B.S.I. Specification, No. 426, 1931.

When selecting a centre size, some allowance must be made for the conditions, such as the number of tools in use at once, the application of steadies, and so on.

Lathe work which must be carried in a chuck sometimes requires a second operation. Given a good chuck of the universal or self-centring type very satisfactory results may be expected. Concentricity near or even within one-thousandth of an inch is possible with a chuck in good condition. The hardened jaws of these chucks are ground in place while the chuck grips a piece of work of a size about the middle of its range. By thus gripping, the working faces of the jaw-screws or scroll are brought into action and the jaws take up their working position. When tightening the jaws for this purpose some makers apply the chuck key to a particular square, which is marked for the purpose.

In using such a chuck afterwards it will be found that the work will run with least eccentricity when the marked square is used for tightening. Accuracy in other parts of the range will depend upon the truth of the jaw-screws and gearing or the scroll.

The Use of Soft Chuck Jaws

For second operation chucking, where the truest possible running is required, jaws with unhardened faces are obtainable. These are clamped on a piece of such dimensions that the jaws are set at the diameter of the work. The shape of the setting piece must be such that the parts of the jaw face, later to be used, may be vacant so that a light cut may be taken over them. Thus true running may be ensured. These soft jaws are commonly used on repetition work, but they are not so well known as they deserve in the general shop. The amount removed in each truing operation is small, and the jaws may have quite a long life even on short runs of work.

The four-jaw chuck still remains one of the most useful accessories for general lathe work. With its aid work may be set with almost any required degree of precision. This is limited only by the patience and skill of the operator. Some men get wonderfully good settings with chalk, but some kind of sensitive indicator is advisable if the very best results are wanted. Suitable indicators are described below, on pp. 78 to 82.

In comparison with the three-jaw self-centring chuck the four-jaw chuck has the advantage that irregular or non-circular work can be set as required with any particular part concentric with the lathe axis. The piece is always lightly gripped with one pair of opposing jaws while it is moved by the other pair. Thus by trial and the use, first, of one pair of jaws and then the other the work is gradually

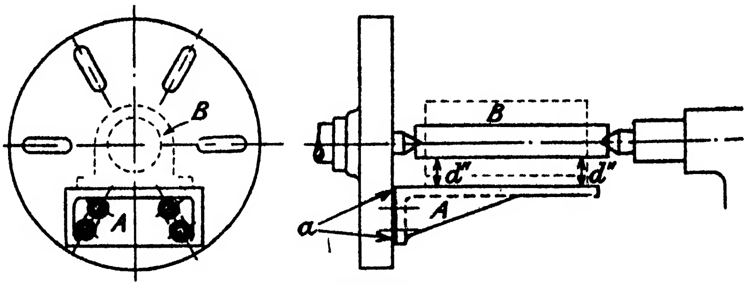


FIG. 48.

brought to the desired position. With a three-jaw chuck, even when the jaws are movable independently, the necessary movement of the jaws is not so easy to determine and the piece is completely free when one jaw is slackened.

When work is to undergo a series of machining operations the first is often the planing or milling of one or two flat surfaces which are then used as an aid to setting for the later operations. If machines are in good condition it is reasonable to expect that the surface and edges of the table are set either perpendicular or parallel to the path of the cutting tool, except where the table is capable of swivelling. The "path of the cutting tool" of course means relatively to the work, and this includes those cases where the work moves and the tool remains still. Fig. 48 shows a convenient set-up for boring a bracket in the lathe at a specified distance from a planed base.

The angle plate A is set at the specified distance from the line of centres by direct measurement from a cylindrical bar carried on the

lathe centres, the measurement d inches plus half the diameter of the bar being made equal to the specified distance. The work is clamped on the angle plate as shown in the dotted outline. If it has already been marked out, its position on the angle plate is easily determined with the aid of the lathe centres. Otherwise it may be set by measurement from the side of the plate. The best method will depend upon the form of the work, and will usually be suggested by it.

Assuming that the machine table is correctly machined and set, it is possible to use its surfaces to place work in position. For the

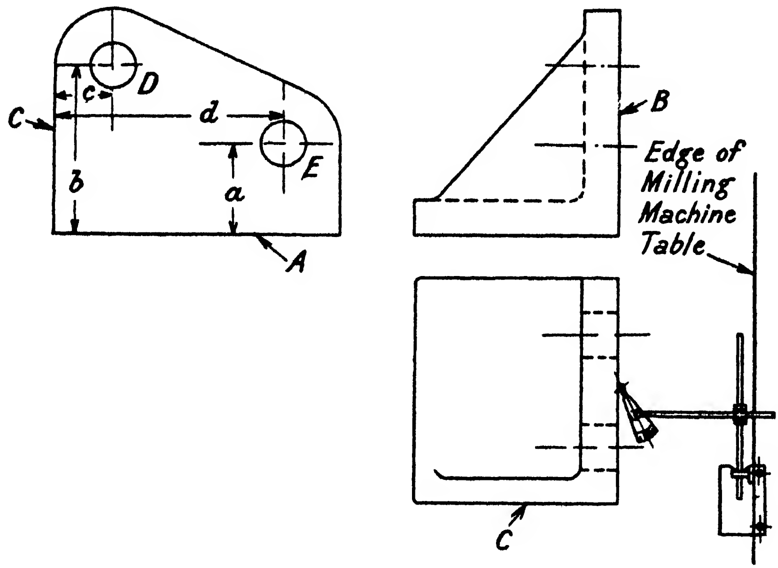


FIG. 49.

ordinary run of work this should be near enough, but for the more important jobs it is better to test the position with an indicator carried in place of the cutting tool, thus eliminating the effect of errors in the machine.

Suppose a bracket, of the form shown in Fig. 49, to have been planed on faces A, B and C. The holes D and E are to be bored parallel to A and perpendicular to B. For this the bracket is taken to the milling machine and the face A set on the table. The face B is then aligned with the edge of the table or with one of the tee-slots as may be more convenient. The alignment may be tested with some form of depth gauge assisted with a thin paper feeler. Alternatively

a surface gauge with pins projecting through the base may be used. The surface gauge should be fitted with an indicator and employed as shown in Fig. 49.

If the machine can be trusted, no greater care than this is needed.

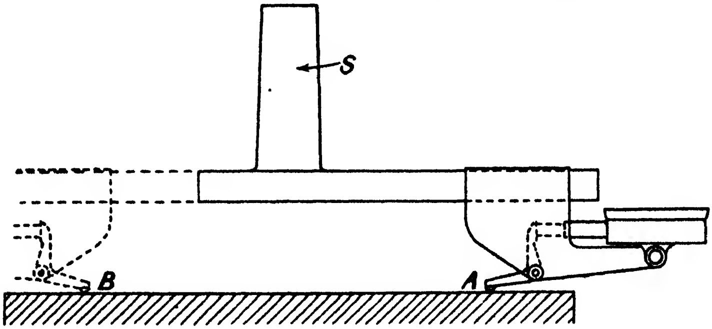


FIG. 50.

But if there is any doubt about the machine the following more direct test should be applied. An indicator is mounted on the machine spindle, by the taper shank S, to rotate at a convenient radius according to the size of the work (see Fig. 50).

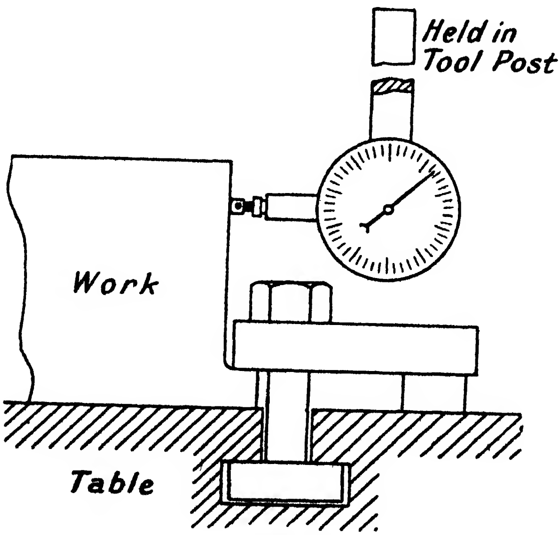


FIG. 51.

Setting Work Square with Spindle

By rotating the machine spindle slowly with the indicator point

in contact with the work from A to B, any deviation from squareness can be detected.

In a similar way, if a casting is to be re-set on a planing machine for a cut parallel to a surface already machined, it may be possible to set by the table surfaces. For exact work it is better to check the position by an indicator held in the tool post. The indicator is placed in contact with the finished surface and run along in contact with it. Correction may then be made with certainty (see Fig. 51).

Angular Settings of Work

A variation of the above which is more often wanted is to set a planed surface at an angle to the direction of the table travel. Some

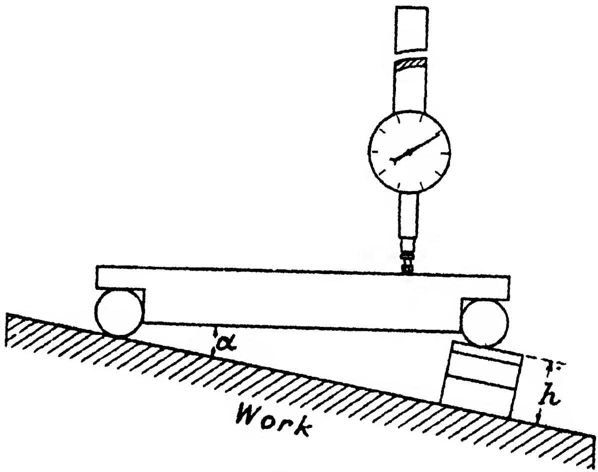


FIG. 52.

kind of protractor or sine bar is set from the finished surface. One arrangement is shown in Fig. 52.

The sine bar A is mounted on distance blocks so that $h \div$length of sine bar$=$sine of angle (α) required.

An indicator carried in the tool post as before then enables the work to be raised on packings until the top edge of the sine bar is parallel to the direction of travel. When this is attained the finished surface of the work will be at the angle required to the surface about to be planed. This description refers to angular settings in the

vertical plane, but the method is equally suitable for settings in the horizontal plane.

The modifications are too obvious to need explanation.

The Use of the Spirit Level

The spirit level has been less used than it deserves as an aid to placing work for machining, possibly because the levels commonly offered for sale are not sufficiently sensitive for good work. But levels are now made by tool-making firms which are fully sensitive enough for any shop purpose. A level in which the bubble moves one-tenth of an inch for an angular motion of the level of twenty seconds is good enough for most purposes in the machine shop. An angle of

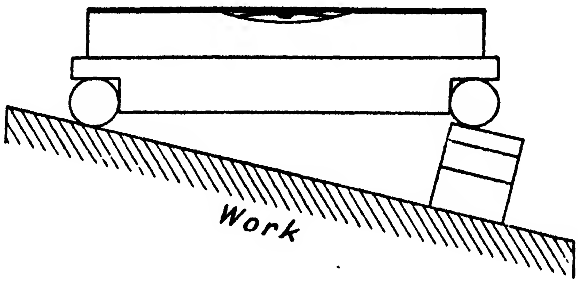


FIG. 53.

twenty seconds is equivalent to that between a 1 foot straight edge and a surface plate, when one end of the straight edge rests on the surface plate and the other end is raised upon a very thin piece of paper, namely, rather more than one-thousandth of an inch. The tube of such a level is ground to a radius of about 85 feet. Still more sensitive levels are made in which one-tenth of an inch movement of the bubble corresponds to angular displacements even so small as three seconds.

The disadvantage of this extreme sensitiveness is the long time required for the bubble to come to rest. There are few occasions on which a "ten-second" level is not adequate. This would have a tube ground to about 170 feet radius.

As usual, high degrees of accuracy in setting require proportionately more time. It is not therefore advisable to select a level which is more sensitive than the work demands.

Precision levels of the kind discussed above are very convenient for setting work for angular planing. In some cases they are handier

than the indicator method just described. The sine bar is applied as before and the work is packed up until the top surface of the sine bar is level. In case the planing machine bed should not be horizontal, the level should be placed on the ways longitudinally and the reading noticed. (See note on the levelling of planing machines in Chapter XVI, p. **303**.) Then the level should be brought to the same reading when it rests on the sine bar. In this way a fault in levelling the bed may be allowed for. Fig. 53 shows the application of the level and the sine bar.

Discs or Cylinders in Angular Settings

As an alternative to the sine bar for angular settings from a machine table the following methods are useful. They may also be used to

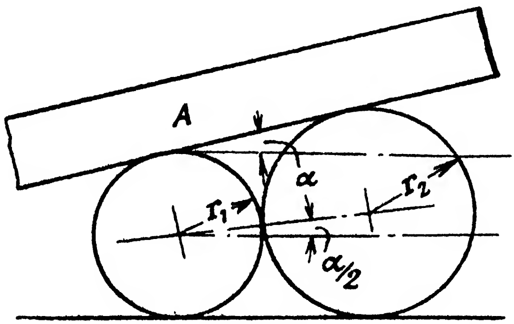


FIG. 54.

set a surface to a specified angle from a spirit level. For the first, which is illustrated in Figs. 54 and 55, two discs or cylinders are

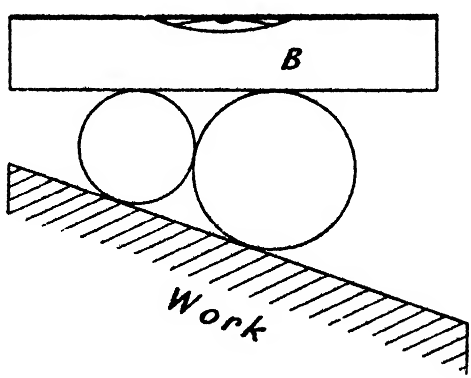


FIG. 55

required. These must be of radii r_1 and r_2, such that $(r_2 - r_1) \div (r_1 + r_2)$ is equal to the sine of half the angle, a required, as shown in Fig. 54. The two cylinders are placed in contact with each other and resting upon the machine table or upon the surface which is to be at an angle a to the horizontal. A straight edge, A, Fig. 54, or a spirit level, B, Fig. 55, resting on the discs will then give the required

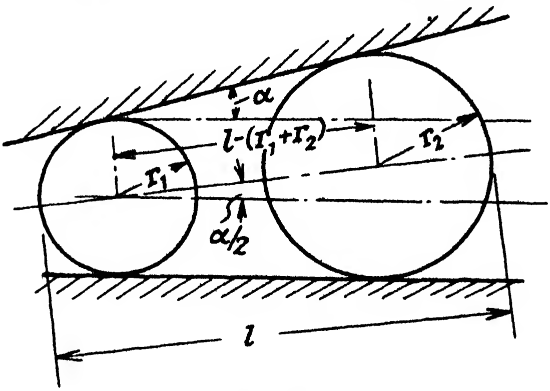


FIG. 56.

setting, with reference to the machine table or the horizontal respectively.

Alternatively the two discs may be set a known distance apart as in Fig. 56. This avoids the need for special discs for every case and gives a longer base line. Sin $a/2 = (r_2 - r_1) \div \{l - (r_1 + r_2)\}$.

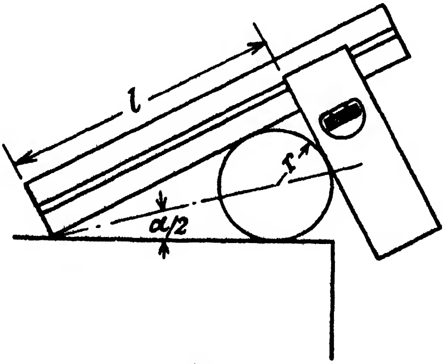


FIG. 57.

A second method, which is even simpler, is shown in Fig. 57. If a square with a fixed blade is used the disc must be of such diameter

$2r$, that $(l-r)$ divided by r, will be equal to the co-tangent of half the angle α required. The disc is placed on the machine table and the square placed upon it so that the disc makes contact with both blade and stock as drawn. The extreme tip of the blade at the same time rests on the machine table.

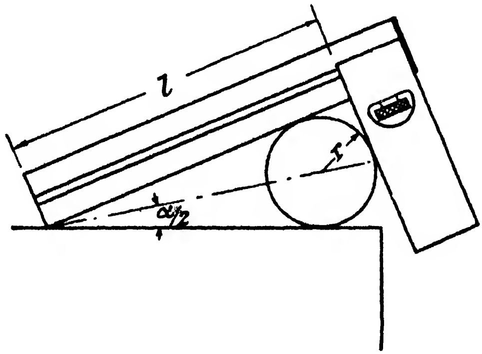


FIG. 58.

If one of the squares with a sliding blade is used there is no need to use a special disc for each setting, since by changing l one disc may give several different angles, as shown in Fig. 58.

Discs are very easily and quickly turned to given sizes, or, better still, if a grinding machine is available they may be ground to size. In either case the size is obtainable within a few ten-thousandths of an inch very quickly. Unless a disc is likely to be used many times

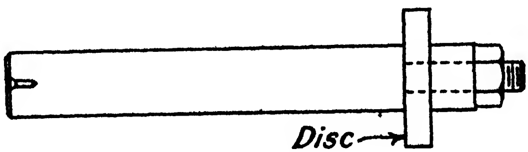


FIG. 59.

it is not necessary to harden it. Discs made to a given size are easily altered to a smaller size for another job, especially if a screwed mandrel such as is shown in Fig. 59 be kept at hand. A mandrel with a collar as drawn is better than one which depends on a fit in the hole of the discs, because it ensures that the discs will be held squarely, which would be difficult without the collar. A very well-designed application of the sine bar to a special job is due to Alfred Herbert, Ltd. The bar is intended for grinding angular setting

blocks to be used in the preparation of thread tools for precision screw cutting. It is drawn in Fig. 60, with the work in position at A. One of the blocks is shown separately in Fig. 61, and in the working position in Fig. 62 at A. The holder for the tool to be

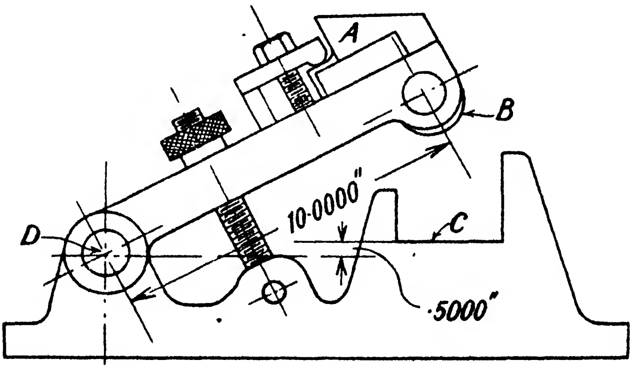


FIG. 60.

ground is shown in Fig. 62. The sine-bar fixture is self-contained, that is, it needs no support from an angle plate. It is some 3 inches in width and is carried on a fixed pivot at the lower end. Ten inches from the centre of this pivot a cylinder B is fixed conveniently above a face C, upon which to rest the distance blocks. This face is

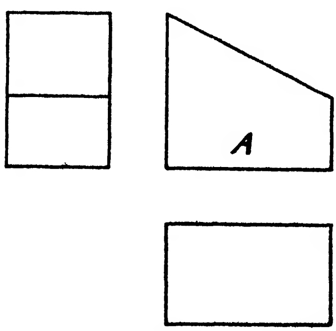


FIG. 61.

offset vertically half an inch above the centre of the permanent pivot. The cylinder B is 1 inch in diameter, so that when it rests directly on the face C the bar is inclined at an angle to the base such that its sine is equal to 0·1000. In other words, there is an initial height of 1 inch which must be deducted from the height of the blocks as calculated. The apparatus is ordinarily used in the surface

grinder although it is robust enough to be used with reasonable care in a shaping machine.

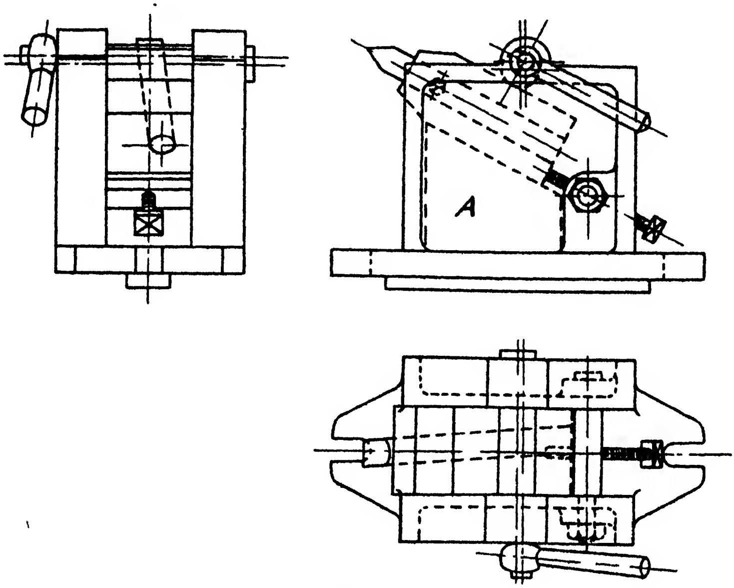


Fig. 62.

Angular Settings by means of Level Protractors

The spirit levels with protractor attachment, made by some of the optical and small tool firms, are extremely handy for direct angular settings. The spirit-level tube is carried in a graduated disc fitted to rotate within the stock. That shown in Fig. 63 is

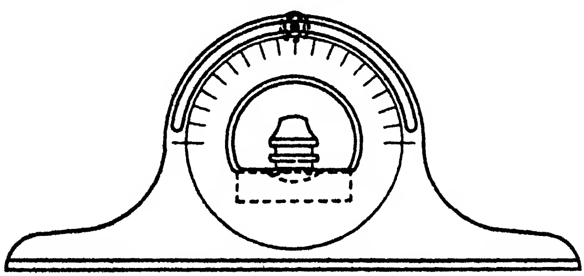


Fig. 63.

made by the L. S. Starrett Co., and is capable of settings to about twelve or fifteen minutes. An instrument of this kind fitted with a

vernier protractor and a level tube of greater radius would enable an accuracy of five minutes to be attained. An elaborated level for angular settings is made by the Bausch and Lomb Co. It is in principle similar to that already described, having a graduated circle rotating within the stock. Setting is made more precise by means of a worm for fine adjustment of the graduated circle. Another convenience is the hinged base which enables the level to be set to zero with the circular scale reading zero, although the surface on which the instrument rests is slightly out of level. Thus if it is desired to set some surface at a given angle to another surface not quite level, the scale reading is set to zero and the bubble is brought to the middle position by means of a levelling screw when the instrument is placed on the reference surface. The level circle is then set to the required angle and the second surface is adjusted until the bubble comes to the mid position. After the initial setting, the hinged base is of course not touched. Thus there is no need to remember a zero correction if the reference surface should not be level.

Centring Level for Use in Milling Machines

It is often necessary to set a milling cutter central with a piece of work, for example, as a preliminary to cutting a keyway in a shaft, or before cutting teeth in a gear blank. The centring level made by Bausch and Lomb is made for this purpose. As may be seen from Fig. 64, it consists of two vees perpendicular to each other, with a level tube A fitted transversely. In use the short vee is placed on, say, the mandrel B carrying the blank to be machined, and the other vee is brought into contact with the cutter C at both sides of the teeth. Assuming the machine to be correctly aligned and levelled, any deviation of the bubble will indicate that the cutter is not central and the necessary adjustment can be made with certainty. Cutters do not usually run with perfect truth. It is therefore advisable to take observations for several positions, the cutter being rotated between readings. Equal deviations on both sides of zero will

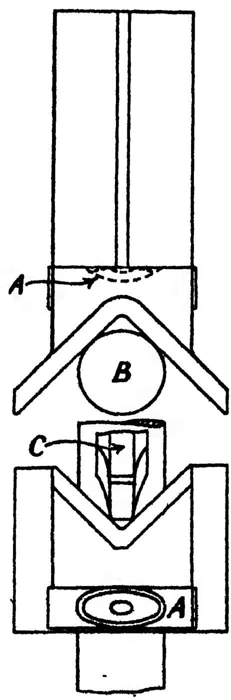


FIG. 64.

indicate that the cutter is central, but the cut will be wider than the cutter thickness if the deviations are perceptible.

Centring Indicator with Level

The appliance shown in Fig. 65 is supplied with Société Genevoise Jig Boring machines for aligning the drilling spindle with the circular table. Within the outer ring A a delicate level tube B is fitted so that the bubble shall be central when the centres above and below are exactly on the vertical axis. After approximately centring, the level is placed between centres in the spindle and in the circular table. The slides of the machine are then used to bring the bubble central in both directions, the instrument being placed first in line with one slide and then in line with the other. Accommodation for adjustment of the centres is provided by the spring plunger C.

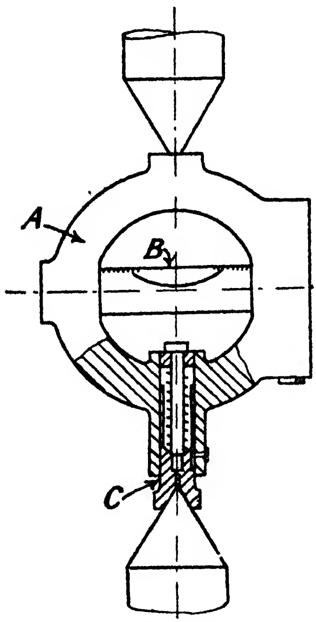


Fig. 65.

Almost from the time when measurements began to be specified to less than one sixty-fourth of an inch, some form of magnifying device has been required for setting work in position and for verifying its accuracy. The number of these devices, known as sensitive indicators, which have been made, shows how strongly the need has been felt and the difficulty of perfectly satisfying it. Sensitive indicators may be divided into two main classes.

There are those which merely indicate deflections from a zero without pretence of measuring it except very roughly. Developed from these is another class, which includes the well-known dial gauge. This second class is designed so that the motion of the pointer is uniformly proportional to the motion of the contact piece over the whole range of the instrument. In the dial gauge the range may be quite large, even as much as two-fifths of an inch.

In some instruments of the measuring class the range may be only

a few thousandths of an inch, but these are usually very sensitive and are designed for greater multiplication.

So many different indicators have been designed that it would be tedious to attempt to describe them all. Those which are described below are selected as being typical of groups. In the majority some form of lever magnification is used. This is simple and direct, but in its simplest forms does not give a uniform scale. The difficulty is overcome in the dial gauge by the use of toothed wheels.

Sensitive Indicators

These instruments are made so that a small motion of the contact face will be shown many times magnified by the indicating pointer. The plunger which carries the contact face is usually held outwards by a spring whose strength is suitable for the pressure desired. Motion of the plunger, which may be anything between a few thousandths of an inch and half an inch, is magnified in many indicators by a system of levers. In other cases an optical form of magnification is used. For many purposes, as when setting a piece of work to rotate truly in a lathe chuck or aligning a job on a planing machine table, it is not of great consequence that the scale of the indicator should be uniform. That is, it is not important that, say, each one-thousandth of an inch of motion of the plunger should move the pointer by a constant quantity. When the correct position of the work is reached the pointer should not move as the work is moved past the plunger, hence the value of the scale divisions does not affect the final setting although the divisions have some value in that they afford a rough idea of the amount of adjustment required during the process of setting. Great accuracy is not needed for this purpose. This point is somewhat emphasised because it appears that even now the great value of simple indicators is hardly realised in general shop work. Possibly the anticipated cost may deter many from using them, but the cost of a simple type is only a few shillings, and such an instrument is adequate for many kinds of setting where the final result depends upon a zero reading.

The accuracy and uniformity of magnification aimed at in more expensive indicators is only necessary when the instrument is to be used as a measuring device to determine the extent of deflections or differences of position. As an example to illustrate the distinction between the two kinds, suppose a machine slide is to be moved through definite distances, an indicator of the dial-gauge type described

below could be used between two stops, one on the fixed part of the machine and one on the slide. The scale of the dial gauge would have to indicate correctly the extent of successive movements of the plunger and would have to be uniform, since several revolutions of the pointer would be needed for any considerable motion of the slide. The mechanism of the gauge would necessarily be of sufficient accuracy to multiply the plunger motion uniformly throughout the required range. As an alternative to the plan outlined above, an inside micrometer might be used in conjunction with a zero indicator which would show deflections without exactly indicating their magnitude. Such a use is described on p. 122 in connection with the Pratt and Whitney jig-boring machine. The indicator is brought to zero for each position.

Although indicators may be obtained to read accurately within a thousandth of an inch over a range of four-tenths of an inch, a very much smaller range is sufficient for many purposes. A range of motion of five to ten-thousandths of an inch is very useful to supplement a set of gauge blocks. These are readily made up in steps of five-thousandths of an inch, and subdivisions of the steps are measured with the indicator, which may be extremely accurate over so small a range. Readings to one ten-thousandth of an inch are quite reliable with a good indicator of the shorter range type. The mechanisms of some typical indicators are described below.

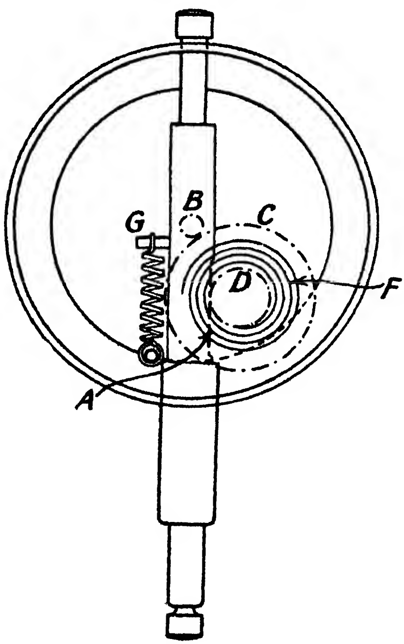


FIG. 66.

The Dial Gauge.—Essentially, gauges of this kind consist of a sliding plunger on one side of which a toothed rack is cut. The rack A meshes with a pinion D. The motion of D is multiplied by a train B, C (Fig. 66). The axis of B carries the pointer which may make several complete revolutions for the full range of the gauge. Backlash is kept always in one

direction by the hair-spring F. A tension spring is applied to the plunger at G to keep it in contact with the work to be gauged.

The Capstan Dial Gauge.—This is an example of a shorter range instrument. It permits a motion of the plunger not exceeding five-hundredths of an inch, which causes only one revolution of the hand. The mechanism is shown in Fig. 67. The plunger acts on an adjustable contact piece A on a pivoted sector B, which meshes with a pinion on the axis of the pointer. The simplification which follows the reduction of the working range is noticeable by comparison with the gauge described above. The adjustment of the gauge by means of the screw C, which varies the distance of the end of the strip A from the pivot, is simple and ingenious. The makers guarantee an accuracy within ±0·0001 inch throughout the range. The effect of backlash is eliminated by a hair-spring on the axis of the pointer. The magnification of the standard pattern is about 120 to 1.

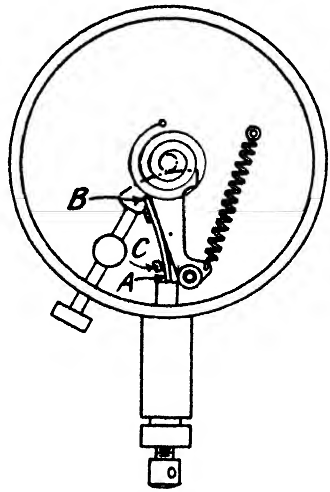


FIG. 67.

The "Talymin" Gauge comparator presents an interesting example of the differential principle for obtaining a high magnification with few and simple parts. It is shown diagrammatically in Fig. 68. Motion of the contact plunger causes the compound roller A to roll on the inclined plane B, and at the same time the pointer moves over the scale. The plunger C is held in its lowest position by a spring, not shown. In use, the plunger is raised and then allowed to make contact with the work by the action of this spring. Another spring which is shown in Fig. 68 serves to keep the bands tight. The multiplication given by this device may be calculated as follows: Suppose the axis of the roller to be fixed, then if the angle through which the roller turns is a radians, the two bands will move downwards a and b inches. That is, the points A and B will be $b-a$ inches farther apart after the motion than they were before (see Fig. 69). But if the end A of one band be fixed in position and the roller be allowed to move bodily as in the instrument, the effect of a pull on the band B will be to cause the roller to

approach A. The relative motion of A and B will remain the same in amount as before, but will all be due to the movement of B, since A

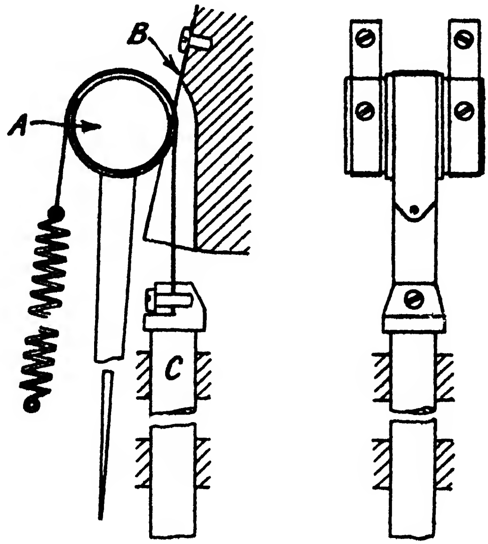


FIG. 68.

is now fixed, *i.e.* the roller moves upwards and B descends $(b-a)$. In the actual design the pointer is about 4 inches long, so that the angular motion of the roller will cause the tip to move through $4a$ inches. By making r_1 and r_2 very nearly equal, it is possible to obtain a very high multiplication. About 400 to 1 is actually used. The scale is graduated in ten-thousandths of an inch, and the whole range of plunger movement is 0·002 inch. Optical methods of magnification are employed in some devices, but these are rather gauging appliances or comparators.

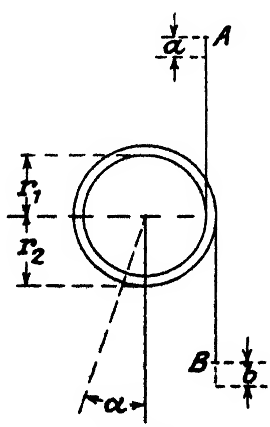


FIG. 69.

The devices described above are measuring instruments. Their scales indicate definite fractions of an inch or other unit. They may be used as indicators, but for many purposes an indicator need not be so carefully designed. One very simple and useful indicator carries a lever mounted near to one end

with a universal joint as shown in Fig. 70. The multiplication is equal to the ratio of the lengths *a* and *b*, which are about $\frac{5}{16}$ inch

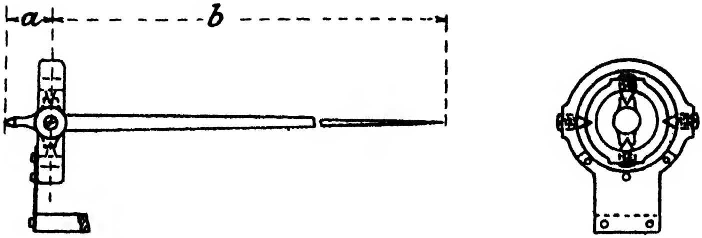


FIG. 70.

and 10 inches respectively. This gives a ratio of 32 to 1, which is high enough for much of the work done in a tool room. The complete freedom of motion of the contact point is an advantage and enables it to be used very conveniently for setting by a punch mark in a rotating piece.

For higher amplification a system of compound levers must be used. Such an arrangement is shown in Fig. 71, which is the indicator made by the Ideal Tool Co., Rochester, New York.

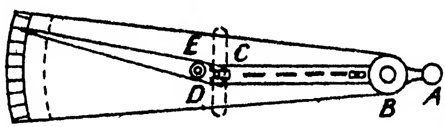


FIG. 71.

Lever A, B and C, pivoted at B, acts by the slot at C on the second lever D, E, pivoted at D. This instrument is graduated in thousandths of an inch.

Centring from a Centre Dot

When a centre for a drilled and bored hole has been set out and centre dotted at the intersection of two lines it is sometimes desirable to use the centre dot as a method of centring the work in the lathe, without the trouble of using a tool-maker's button (see p. 108). Provided the position has been carefully set out and afterwards dotted with the centre punch described on p. 53, very accurate work, almost, if not quite, equal to that of the button method, may be done. As the centre dot will be small, it is not easy to apply an

indicator directly. The tool shown in Fig. 72 is then useful. It consists of a plain cylindrical piece, A, ground at one end to a conical point which should be hardened and fitted at the other end with a spring plunger, B, carrying a hollow centre. The outer surface of the

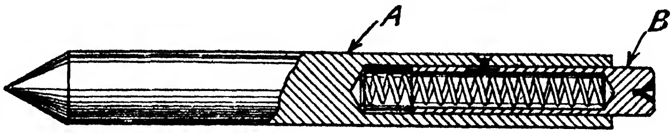


FIG. 72.

cylinder and the centres at the ends should all be very precisely finished so that they will be concentric—preferably by taking a light finishing cut over the outside after the parts have been fitted together and when the bar is running on its own centres. Care must be taken to make sure that the bore in which the plunger slides is finished truly in line with the axis, otherwise the sliding centre will only be true for one position of the plunger. The bar should be run in a steady for boring to ensure this. When the tool is finished it is applied to the work in the manner shown in Fig. 73, being held in

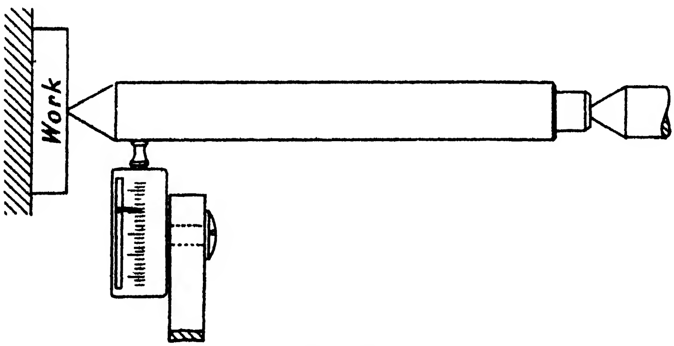


FIG. 73.

position by lightly compressing the spring behind the plunger. Any fault in setting the work on the face plate will be shown distinctly by the indicator as the work is rotated.

Applications of Optical Methods to Machine Work

These applications are of most use when it is not convenient to use a sensitive indicator of the usual kind for setting or correcting. They are particularly useful in tests where a straight line of reference

is required, which may be difficult to provide in material form. The type of instrument used may vary from a microscope to a telescope according to the distances involved.

As an example of the use of a microscope, suppose a plate has been carefully marked out with very fine lines at whose intersections holes are to be bored. A microscope with cross-hairs may be mounted by the bar, C, on the tool holder of the slide rest of a lathe with screw adjustment A of the vertical slide B in Fig. 74. Horizontal adjustments are made with the slide rest of the lathe. The plate to be bored is held in a four-jaw chuck or is strapped to the face plate. By observation of the intersection of the lines on the work, as the face plate is slowly rotated the microscope may be set in line with the axis of the lathe spindle. The work may then be adjusted until the intersection of the marking lines coincides with

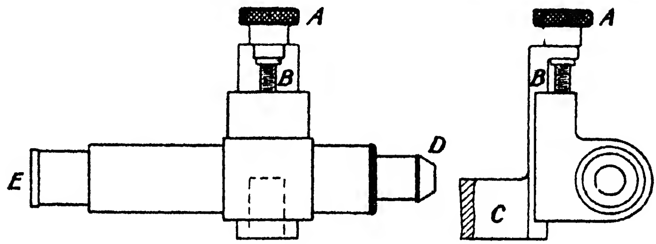


FIG. 74.

the cross-hair intersection in the microscope. Where the method is often used a special fitting to set the microscope concentrically with the lathe axis will save much of the time of setting as described above. For this purpose a microscope mounted on a taper shank fitting the tailstock socket in place of the usual centre is convenient, but the miscroscope must then be provided with prisms to deflect the line of sight so that the eye piece is out of the line of centres. An arrangement of the kind is used in the S.I.P. jig boring machine. The microscope being correctly placed, it only remains to place the work so that the required point lies in the axis of the microscope. A very high degree of magnification is not required; from 20 up to 50 diameters should cover most shop requirements. At 25 diameters an error of one-thousandth of an inch in centring would appear as one-fortieth of an inch when viewed through the eyepiece E of the microscope. An error in coincidence much less than this can be observed provided the lines are suitable. The question of the quality of lines

used in marking out is discussed in Chapter IV. It may be remarked here that if precautions are taken in marking out and in using the microscope, results of an accuracy approaching that of the button method may be attained in rather less time than is needed for that method. The microscope used for this purpose should have an objective D with a focal length between 1 inch and 2 inches. This will permit the microscope to be placed conveniently with regard to the work.

A device, which was primarily designed for lining up locomotive and large horizontal engines, is made by Carl Zeiss of Jena. It has obviously other applications, such as the alignment of large machine tools and similar work. The instrument consists of two parts, as shown in the upper view of Fig. 75. At the right-hand side there is a collimator having two glass discs each engraved with two scales perpendicular to each other and crossing at the centre of the disc. One of these graduated discs is situated at G at the left-hand end of

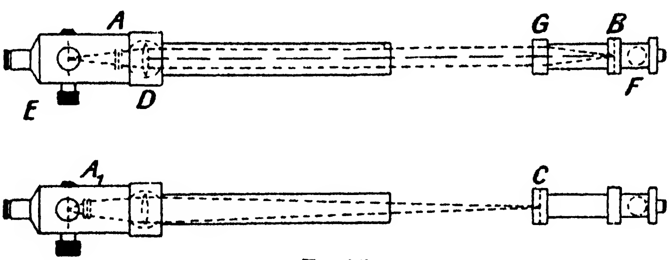


FIG. 75.

the collimator. The other is at B in the focal plane of a lens placed just at the right of the disc at G. A lamp at F is used for illuminating either disc. The other part of the instrument is a telescope arranged so that an image of either graduated disc may be formed in the plane of cross-webs which are placed so that they and the image of the scale can be observed by means of the eyepiece. The objective system of this telescope is mounted on a spherical bearing at D and is adjustable to any required angular position relatively to the eyepiece and the outer casing by means of two perpendicular micrometer screws at E. To explain the use of the instrument, suppose it is required to place the axes of two bored holes in the same straight line.

The telescope and collimator are placed in the bored holes to be aligned, one part in each hole, each part being set concentrically with the corresponding hole by means of suitable bushings or by adjustable

spiders. The locating surfaces for any particular case depend upon the form of the part. The essential thing is to hold the collimator and telescope in line with the respective machine members.

When the instrument is in place the lining up proceeds in two stages. First the holes are set parallel as follows. The telescope is focussed to view the graduated disc situated at B. By the action of the lens at G the light from the disc B is caused to enter the telescope as a parallel beam and the effect is that the scales at B are viewed as though they were at an infinite distance. Thus a lateral motion of the collimator will not perceptibly move the image of the scales provided it is not accompanied by any change of direction, which would, of course, swing the beam of light across the field of the telescope. With the telescope focussed in the way described and as illustrated diagrammatically in the upper part of Fig. 75, one member or the other must be tilted until the crossed scales at B in the collimator appear to coincide with the cross-webs in the eyepiece of the telescope, that is, the zero of each scale must lie on the intersection of the cross-webs. It may be necessary to move both members before their axes become parallel. If, for example, that carrying the telescope is out of line, the correction needed may be found by setting the telescope with the aid of the micrometer screws until it lies in the right direction. The micrometer readings will then indicate the movement required to correct the direction. After correction the telescope must be in line when the micrometers are both set to zero. Similarly, if the collimator is out of the true direction the error will be indicated by the deviation of the scale zeros from the point of intersection of the cross-webs, the telescope being set centrally in its holder.

When adjustments have been made as described, the axes of the two holes will be parallel but not necessarily in the same straight line.

Coincidence of the axes is obtained in the second stage of the process, which is as follows. The lenses of the telescope are adjusted to bring the nearer disc of the collimator into focus. This disc is viewed without the intervention of the collimator lens at G. The arrangement is shown diagrammatically in the lower view of Fig. 75. As will be seen, this method of use permits the graduated disc to be observed as though it were at a comparatively short distance from the telescope, not, as in the other method, as if it were at an infinite distance. Consequently any lateral motion of the collimator parallel to itself will be perceptible, since it will cause the image of the scales to move relatively to the cross-webs in the eyepiece. It is a con-

venient feature that the actual displacement can be read from the scales, as this enables adjustment to be made with confidence. The purpose of such adjustment is to bring the zeros of the two scales into coincidence with the intersection of the cross-webs by a motion of either member parallel to itself. When the two parts are set truly in line, it will be possible to focus the telescope on either graduated disc without displacing the scale zeros from the cross-web intersection.

The foregoing explanation has been based on the assumption that two holes were to be aligned, but the use of the apparatus is not limited to that case. Any two members may be set up provided suitable fixtures are used to attach the telescope and collimator in definitely known positions in relation to the parts; for example, the telescope may be set by adjustable spiders in line with an engine cylinder and the collimator may be mounted in line with the guide bars and at a known distance from them. The distance should be such that, when the slide bars are in the right position the collimator and the telescope will be in line. Where the amount of work done is sufficient to justify the outlay, the optical method of setting is a great improvement on the method of measurements from a stretched wire, both in accuracy and time.

A form of optical instrument of great value in testing the alignment of surfaces and in setting up work in position for machining is the auto-collimating telescope (Fig. 76). In this a beam of light is caused to illuminate cross-hairs or scales placed in the focal plane of the objective lens. Thus a plane reflecting surface situated in a prolongation of the axis of the telescope will reflect the light backwards, and if the reflecting surface is nearly perpendicular to the axis an image will be formed near to the original lines. The distance between the original lines and the image formed by reflection will depend upon the inclination of the reflecting surface to the optical axis. If the surface is perpendicular to the axis the image will coincide with the actual lines. The displacement of the image enables the deviation from perpendicularity to be estimated. In a telescope made by Adam Hilger, Ltd., the cross-lines are divided into forty or fifty divisions, each of which indicates an inclination of one minute. These are viewed through an eyepiece and appear of such a size that they may be subdivided by estimation into fifths. One application of an instrument such as this is to set a surface square with an axis of rotation. The surface to be set need not be smooth enough to reflect

light provided a parallel glass plate can be attached to it. When this has been done the telescope is set up so that the image of the cross-hairs reflected back to the eyepiece coincides with the cross-hairs. If the surface is not square with the axis of rotation a partial rotation will cause the image to move. By adjustment and re-trial a position may be found for which there will be no deviation of the image as the work is rotated.

A similar arrangement is useful for testing the working surfaces of machine slides. A stainless steel cube, with one face optically worked to form a plane reflector, is placed on the surface to be tested at various distances from the telescope. If the slide is truly plane the position of the image should be constant for all positions of the cube along the slide (see Fig. 76). If it is inaccurate for any

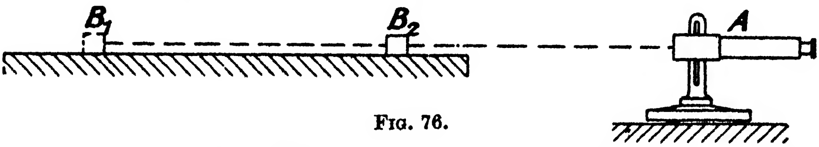


FIG. 76.

reason, such as wear, there will be positions at which the cube will tilt slightly and the image will be deflected. As an example, a tilt might be expected where a much used part of a slide met an almost unworn part. A sudden change would of course be more easily perceptible by this method than would a very gradual change. Also the smaller the cube the more delicate the test, since local changes of angle would be shown up, whereas a larger cube would tend to average out the variations in the same way that the motion of a long slide is likely to be more accurate than either of the sliding surfaces concerned.

Microscope with Cross-webs for Tool-setting

A microscope with cross-hairs adjustable in their angular positions is very useful for setting screw-cutting tools correctly with regard to the work. It may be attached to a vee block, so that by placing it on a cylindrical bar between centres the position of the microscope is definitely known with regard to the work. The microscope is then conveniently situated over the screw-cutting tool; if the cross-webs have been correctly set to the required thread angle it is possible to verify the shape of the tool *e* and to set it symmetrically with regard to the work by the cross-

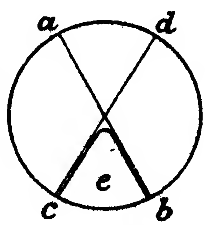


FIG. 77.

webs *ab* and *cd* (see Fig. 77). The sharp tool edges provide definite lines for observations, and very close settings are possible with low magnifications up to 15 diameters.

A variation of the method has been adopted by one of the optical instrument firms (Bausch & Lomb). The vee block, which is placed upon the work, or alternatively upon a cylindrical bar between centres, carries a thread gauge or template A, Fig. 78, of a suitable thread angle set square with the vee so that it will be at about centre height. Above this a lens or low-power microscope is carried. The gauge and tool may thus be very easily examined and the tool correctly set. About 4 diameters is a sufficient magnification, as the observation is made on the light passing between the tool and the gauge from a reflecting surface below. Very slight variations in the width of the light are readily perceptible. It may be remarked that as a

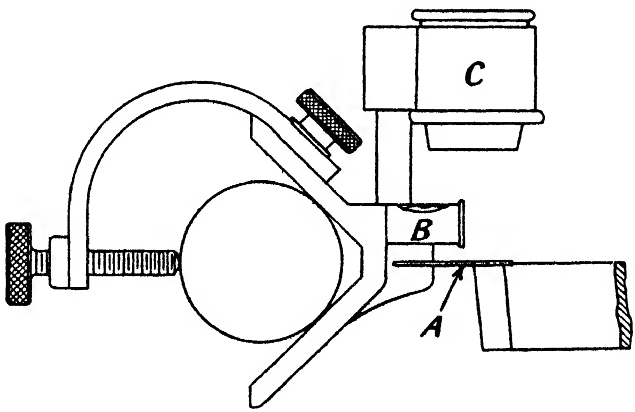


FIG. 78.

rule the use of a higher power than is really necessary is not an advantage as it tends to require more delicacy in use and so occupies time without any corresponding gain. To ensure that the gauge is at centre height a transverse spirit level is attached to the vee as at B (Fig. 78).

Another very interesting optical application is in the design of dividing head made by Carl Zeiss for milling machines and for general tool-room work. In this head there is attached to the work spindle a finely divided circle which is observed through a microscope. A worm is used for rotating the work spindle, but this is merely for fine adjustment and does not determine the position of

the work spindle as would be the case if the usual dividing plate were used. The accuracy claimed for the optical design of head is 5 to 10 seconds, which may be compared with about 30 or 40 seconds of the more usual head with the dividing plate. In making the comparison it should be remembered that the first is not subject to deterioration by wear, whereas the second is. This dividing head is described more fully in Chapter IX.

For the alignment and setting of machine parts over comparatively long distances a simple form of surveyor's level is useful. One application of this kind is to test the alignment of line shafting, especially in the vertical plane. The level is set to sight in the required direction at a convenient distance from the line shaft. The line of sight may usually be at some distance below the shafting so that obstructions may be avoided. A target is hung at a constant distance from the shaft at points near each bearing in turn, and is sighted with the level set horizontally. To check the setting in the horizontal plane a slightly different form of target projecting laterally should be used so that the error introduced by failure to hang the target level will have but little effect on the reading.

The method might be adapted to the alignment of large work in general. At present this is usually done with the aid of a stretched wire, which is satisfactory for testing alignment in the horizontal plane, but requires a correction for sag in the vertical plane. Although with fine wire under heavy tension the sag may be reduced to a very small quantity, it still remains large enough to be taken into account over all but the shorter distances.

CHAPTER VI

LOCATION OF WORK

THE object of repetition machine work is essentially the production of numbers of pieces which are to be similar in all important dimensions. This means that the significant surfaces of each piece must be placed in the same relation in all the pieces. In a turned piece it usually involves concentricity of all the diameters as well as equality of diameters and lengths for all the pieces of a batch. Where turned work is finished in a single operation from the bar as in a turret or capstan lathe, the question of setting presents no great difficulty, since the piece continues to rotate on the one axis throughout the machining operation and, provided reasonable care is taken, the different parts will be concentric. It does sometimes happen that pieces are of such form that they cannot be completely finished at one setting, usually because part of the surface to be turned must be used in gripping the part. The work must then be rechucked by a surface already finished in order to complete the work, but with ordinary precautions almost perfect concentricity may be secured. The use of soft chuck jaws bored or surfaced when in the working position is very effective for second operation work. This method is referred to at greater length on p. 64, Chapter V.

Work which is turned on centres is easy to reproduce within almost any degree of similarity, given well-formed centres in the work and a true running centre in the lathe. There is nowadays a strong tendency to use special centre lathes for work in which concentricity is important. Not only is the turning likely to be of greater precision, but if the parts are to be finished by grinding, as is not uncommon, it is a distinct advantage to have the centres in the work ready for the finishing operation. Manufacturing type centre lathes are fitted with a number of tool holders and adequate steady rests so that the rate of metal removal may be quite high without any sacrifice of accuracy. The use of several tools avoids the necessity of resetting for each piece of work. Each diameter of the work is turned by its own tool, which once set need not be disturbed except for resharpening. At the same time the distances between the

tools in a direction parallel to the lathe axis will determine the length of the part turned to each diameter. With a suitably designed lathe used in this way remarkable constancy of dimensions can be maintained throughout the production of large batches of turned pieces.

At this point it may be well to mention that the addition of cutting tools, all operating simultaneously, should be done with caution. In ordinary turning with a single tool there is rarely any need to consider the torsional strength of the work, since other factors usually set a limit to the torque well below the shear strength of the material. But in lathes especially designed for multiple cutting there is ample power and a large number of steady rests minimises the effect of bending. Therefore there is some danger that one tool may be added after another until the total resistance to turning is very great. If it should also happen that the driving torque must be transmitted through a part of the component of comparatively small diameter, the shear stress in the material may approach or even exceed the safe limit. Immediate failure is not the greatest risk. It is even worse that a piece should pass into service in such a condition through overstress that failure will probably occur after a period of normal work. A fault of this kind may be concealed until after failure and may not be suspected as the cause even then.

This warning is not intended as a condemnation of multiple tooling, which may be employed with perfect safety in a very large proportion of jobs. Caution should be used when there is a tendency to remove material by multiple heavy cuts at moderate speeds, especially if there is much variation in the diameter of the work. Lighter cuts at higher speeds need involve but little sacrifice of output, especially if full advantage be taken of the newer cutting alloys, and will avoid the imposition of excessive stress. These new alloys are most effective in taking light cuts at high speed, so that they maintain a satisfactory output under the conditions most favourable to accurate, well-finished work.

Location by Centre Points

If repetition work produced on the lathe by multiple tools as above described be analysed, it will be found that interchangeability depends upon several factors. The work itself is definitely located by means of the two centres which determine its axis of rotation. The endlong position of the work relatively to the cutting tools, or rather to the limits of travel of the cutting tools, is also fixed by the

two centres. The cutting tools are traversed in paths fixed relatively to the centres of the lathe and remove all metal which encroaches upon those paths. Provided the stresses in the work and the machine parts can be kept low enough to prevent appreciable yielding the method is very successful. Stated briefly, it consists in locating the work with regard to cutting tools which remove all metal situated outside the finished boundary surfaces.

With detail modifications in the method of locating the work the same principle underlies the application of jigs and fixtures for the manufacture of interchangeable parts. These commonly appear to be more complex than the method described for lathe work. But actually all well-designed jigs are found to depend upon the same simple principle when they are analysed, although an appearance of complication may be given to them by the necessity to enclose, to a greater or less extent, the work which they locate.

Before considering the details of jigs and fixtures a little attention should be given to the analysis of a complex motion into its elements. The related question of limiting or restricting motion will be simplified by this preliminary thought. It is this related question upon which the design of jigs depends.

Possible Motions of a Point and a Body

Suppose a casting to be resting in space, being, for example, suspended from an overhead travelling crane. It is then conveniently situated to be moved in any direction whatever. But motion in any direction which may be given to it can be resolved into three component motions; in fact, must be if it is to be moved by the crane, since the crab of the crane has motion along the moving beam, which in turn moves in a perpendicular direction along the side girders. Vertical movement of the casting is possible by raising or lowering it by means of the crane chain. If now the casting is originally in the centre of the shed at 10 feet above the floor, and it is desired to place it on the floor in one corner of the shed, the movement could be made in two ways. First the crab, and the casting with it, could be taken to one end of the cross-beam of the crane. Then the cross-beam could be moved to the end of the shed and the casting finally lowered to the floor. Thus the required change of position would have been accomplished in three stages, one after another.

But if all three motions had occurred at the same time the casting could have been made to follow a straight path from its initial position

to its destination. Obviously the same component motions would have been present, but they would all have been combined to act as the single resultant motion of the casting, by which it would proceed directly to its destination. Any possible movement of the casting bodily from one point to another could be resolved into the same three components.

Degrees of Freedom

So far the casting has been regarded as a point, that point being its centre of gravity. As far as a point is concerned there is no need

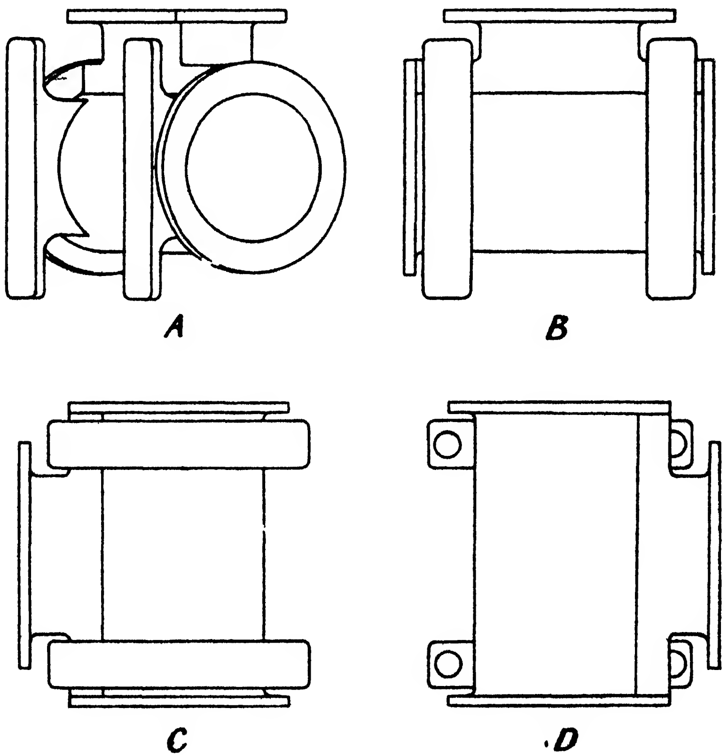


Fig. 79.

to consider questions of rotation, since the ideal point has no dimensions and consequently all its aspects are alike. An actual casting would, as a rule, have different dimensions in different directions. It would therefore be necessary to arrange it in some particular way in its final position. To do this a rotational movement would most

likely be required. No matter what this motion might be, it could be resolved into three component rotations about three mutually perpendicular axes. As an illustration, suppose the casting already discussed to be the cylinder for a horizontal engine: it is, say, originally slung with its centre line inclined at 60° to the horizontal, crossways of the shop and with its feet on the upper side, as in Fig. 79, A. This cylinder casting is to be set in a horizontal boring machine so that its feet rest on the table of the machine, with its centre line in line with the spindle of the machine, that is, along the shop. Assume the casting to be suspended from the crane so that a short fall will bring it to the machine table.

A partial turn about a horizontal axis will bring the casting into a horizontal position but still across the shop as at B. A quarter turn about a vertical axis is required to place the casting in the right direction along the shop as at C, though it will still be upside down. A half turn about a second horizontal axis parallel to the length of the shop will set the casting correctly on its feet as at D. Thus partial rotations about three perpendicular axes have brought the cylinder to the required position. These rotations are additional to the movements required to bring it bodily to the boring machine.

Examination of any other possible change of position of a body will show that it may be accomplished by six elementary movements, namely, three motions bodily in directions perpendicular to each other and three rotational motions about three axes perpendicular to each other. The absence of any one of these six possible motions will entail a certain loss of freedom. Perfect freedom means that all these six movements are permissible.

This is sometimes expressed by saying that a body may have six degrees of freedom. The meaning of this statement is that any possible motion of a body may be resolved into not more than six component motions. Less than six may be necessary in some cases, but there is no possible motion which requires more than six components for its reproduction.

Restriction of Motion

For the jig and fixture designer the problem is usually to provide means for restricting motion with certainty, so that each one of a series of similar castings may be brought to rest in turn in exactly the same position. This purpose is accomplished by providing the fixture with a suitable number of contact pieces or stops, so placed

that, when the casting has made contact with them all, no further motion is possible. The analysis of motion made above is worthy of consideration, although at first sight it may seem elementary. It is, however, very important to realise what motions are possible and to provide only the minimum essential number of points to limit these motions, since additional contacts beyond the essential minimum number do not give greater surety but rather introduce doubt. Suppose a simple cylindrical rod to be required to rest in a series of three vee notches A, B and C with one end of the rod against an end stop D, as in Fig. 80. If the notches are perfectly aligned with each

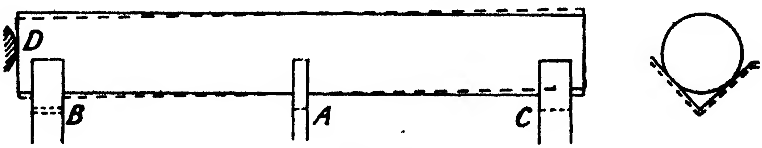


FIG. 80.

other there will be only one possible motion of the rod, namely, a rotation about its own axis. But if the central notch A is slightly higher than the other two the rod will be able to rock about the central notch. It will make contact then with only one of the end notches. Much greater positiveness would be secured if the central vee were to be removed, thus reducing the number of possible contact faces from seven to five. The location of the cylinder would not then depend upon the perfection of alignment of the three vees. The two remaining vees need not even be machined. They would act quite well in the rough state.

Geometric Slides

In the example quoted above it will be noticed that five contact faces are mentioned, two on each of the two vee notches and one end stop. Also it was said that the only possible motion of the cylinder, so long as it remained in contact with the five faces, would be a rotation about its own axis. It could then be said to have one degree of freedom or, conversely, to have lost five degrees of freedom. If the end stop were removed, the cylinder would be able to slide longitudinally, thus having acquired an additional degree of freedom.

Examination of a number of cases will show that as a rule each suitably placed contact face, up to and including the sixth, will eliminate one degree of freedom. Emphasis must be put upon the word "suitably" in the above statement, because it is possible to

add contact faces in such a way as to cause no restriction of freedom. For example, the third vee in the case quoted was not able to fix the cylinder any more definitely than two vees. The contacts which it provided were merely duplicating those already in existence. Complete fixation of the cylinder would require some device such as a perpendicularly projecting pin resting on a sixth contact face. Thus

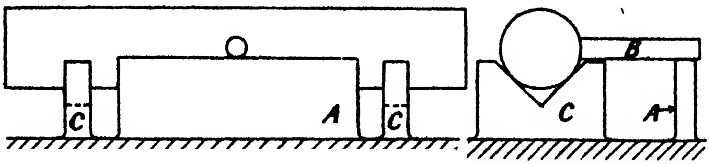


FIG. 81.

rotation of the cylinder would be prevented and the last degree of freedom would be removed.

If the end stop were taken away and a straight edge A were fixed to the vees C parallel to the axis of the cylinder at such a distance that the projecting pin B could rest upon it, the mechanism so obtained would be an example of the geometric slide, permitting movement in one direction only (see Fig. 81). For loads which can be supported

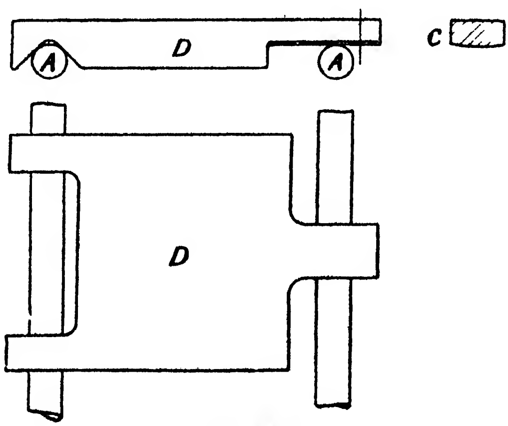


FIG. 82.

by point contacts or, more correctly, by very small surfaces, the geometric slide is ideal. It involves very little machining, and that of the simplest kind. In its definition of motion it is perfect. Fig. 82 shows a very simply made geometric slide consisting of two parallel

ground cylindrical rods A clamped to a base plate. On these a casting, D, rests by two vees and a projecting arm, shown in cross-section at C. Given the parallel rods, which are very easily made, no other machining is necessary. If the rods are ground on dead centres in the usual way they will be straight when the diameter is constant from end to end.

The above examples have been discussed at some length in order to make clear the action of contacts in restricting freedom. To sum up the whole matter, consider a tripod stand (an ordinary chemical tripod, for example) with the legs terminating in round knobs of, say, half an inch diameter. Imagine this tripod to be hovering in space above a horizontal table. It has for the moment all possible freedom —it can move in any direction and it can rotate about any axis. Next suppose one of the feet to be kept upon the table. Movement vertically is now impossible, but any horizontal movement may be made and at least partial rotation about any axis. One contact has been made and one degree of freedom sacrificed. As each of the remaining feet is brought down to the table top, first one and then another possible rotation is lost, leaving only rotation about a vertical axis and translation in any direction in a horizontal plane. If now a vertical plane be fixed to some part of the table top, and a side of one of the three feet be maintained in contact with it, still keeping the other contacts unbroken, there will be four contacts. The tripod may slide over the table in a direction parallel to the vertical face, and it may partially rotate about a vertical axis passing through the foot which touches the vertical face. That is, one translation and one rotation only are left. The last rotation is lost when a second foot is kept against the vertical plane. Finally, the last possibility of translation, namely, in a horizontal direction parallel to the vertical plane, will disappear when one of the feet is kept against a second fixed vertical plane perpendicular to the first.

These elementary principles must be followed, whether consciously or not, in all good jig design. The principle which governs the satisfactory location of the necessary six contact or bearing points was enunciated by Clerk Maxwell in 1876, in the following words: "If one of the bearings was removed, the direction in which the corresponding point of the instrument would be left free to move by other bearings must be as nearly as possible normal to the tangent plane at the bearing."

Problems of Location

Such a disposition of the contact faces will enable the location to be defined with the smallest possible forces or stresses in the parts, since there will be no wedging action; that is, possible movements are each resisted by planes perpendicular to their direction. Also a given chip or similar obstruction will cause least error between surfaces perpendicular to the direction of motion. Compare A and B, Fig. 83.

When a number of similar castings, forgings or other roughly shaped parts are to be machined, it is important as a rule that the surfaces to be finished shall be machined in some particular position in regard to certain rough parts of the piece. Important thicknesses

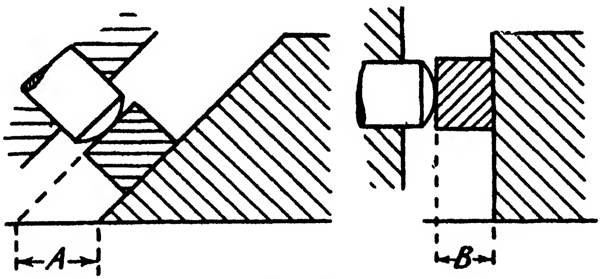


Fig. 83.

of metal can be controlled by the choice of locating surfaces, as, for example, in setting up a cylinder for boring. If this were set by the outside of the cylinder the walls would be nearly uniform in thickness. Whatever the controlling factor may be, a careful choice of locating points will usually enable requirements to be satisfied, in spite of normal variations of the rough components from standard size. The jig or fixture will automatically bring the components into the correct position with regard to the cutting tools without preliminary marking out. The machined parts will then be interchangeable, since the variations, if any, will be limited to the less important dimensions. The advantages of the method as compared with marking out are (*a*) a very great saving of time, and (*b*) interchangeability.

Before discussing a few actual jigs and fixtures, the items of clamping and provision of additional support to resist machining forces may be mentioned. Many parts will no doubt occur to the mind for which six contact points or small surfaces would be quite insufficient to provide support. But these essential six are those points

which are fixed. They determine the position of the component. After that has been established there is no objection to bringing additional supports into contact with the piece and locking them in place. These supplementary supports take their position from the already fixed component and they must not be permitted to displace it in any way. Their purpose is merely to prevent displacement of the piece by forces applied in cutting. The avoidance of distortion or spring is a guiding principle in the design of clamps. Whenever possible a clamp should act through solid metal directly on to a supporting face. Many cases have arisen in which the pressure of clamping has bent or twisted the work. Machining done under such conditions is defective because the part springs back when the clamps are released and the finished surfaces become bent or warped.

The more elaborate fixtures may be introduced by a discussion of a few simple applications of standard appliances to ensure definite location.

A job which often occurs is to plane a block of metal so that two adjacent faces are square with each other. If the piece can be

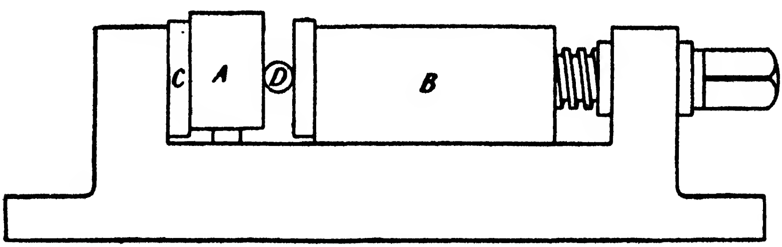


FIG. 84.

clamped so that the two faces are both clear for machining at once, there is no great difficulty in squaring them, by planing or shaping. Since the piece is only clamped once, the result will depend upon the correctness of the horizontal and vertical slides of the machine. For various reasons, it may not always be possible to plane the two sides at one setting. Then the work, having been planed on one horizontal face, must be reset with that face vertical, either by packing up from the table, bolting to a vertical angle plate or by gripping in a vice. In the first two cases the surface already planed is definitely placed vertically. In the third case there may be some doubt about the location. For example, which of the two vice jaws is actually used to determine the position? Even in a well-adjusted vice the

moving jaw is very likely to rock slightly. The fixed jaw C will therefore be tested and set vertically. Then in clamping the work care must be taken that the fixed jaw controls the alignment of the already finished side. The simplest way of doing this is to localise the contact of the moving jaw by inserting a round bar D horizontally between it and the work A (Fig. 84). Any attempt to use the whole surface of the moving jaw is almost sure to produce work which is not square, since the work is just as likely to set itself by the moving jaw as by the fixed jaw. In practice, the setting of any particular piece will depend partly on the play permitted in the moving jaw slide and partly upon the shape of the piece. The latter is likely to vary in a series of pieces, whether castings or forgings, and the results of planing a batch will be variable unless the contact is limited to a line as suggested. For tests on squareness of tool slides, see Chapter XVI.

Value of Surface Support for Machined Work

When the principal surfaces of a component have been machined and there still remain further operations, it may not be necessary to limit the contacts to small surfaces. It will usually be preferable to use comparatively large surfaces, such as a large planed area resting on a machine table. The reason for this is twofold. Between two true surfaces there is no tendency to rock and consequently no uncertainty of position. The existence of any rocking motion between two plane surfaces is a useful warning that some foreign matter has been left between them. When the contact is limited to the minimum number of small areas the casting may appear to stand firmly even though the surfaces are not clear. Special care must therefore be exercised to clean all limited contact areas, otherwise the result may be a misplaced casting which will fail to clean up.

Typical Fixtures

A simple jig which embodies several important principles is drawn in Fig. 85. The work is a connecting rod which has already been straddle milled to thickness on the ends. This preliminary straddle milling operation is controlled by a fixture which locates the part so that the ends will be symmetrical with regard to the rod. The jig shown is therefore intended to deal with partly finished work, and is designed with contact surfaces as well as contact points. After withdrawing the sliding block A, a rod is inserted sideways into the

jig with a face of the big end on the top of the hollow boss B. In case the small ends should vary in thickness the supporting bush C is screwed downwards to clear. Then the sliding bush D is closed down on the big end to hold it lightly while the block A is screwed up to centre the rod against the contact points E. The fixed vee formed by E and the sliding vee A bear on unfinished surfaces and are therefore limited to point contacts. When the rod is set by the vees, the sliding bush D is finally clamped to hold the big end firmly. Bush C is then screwed up just into contact with the small end and

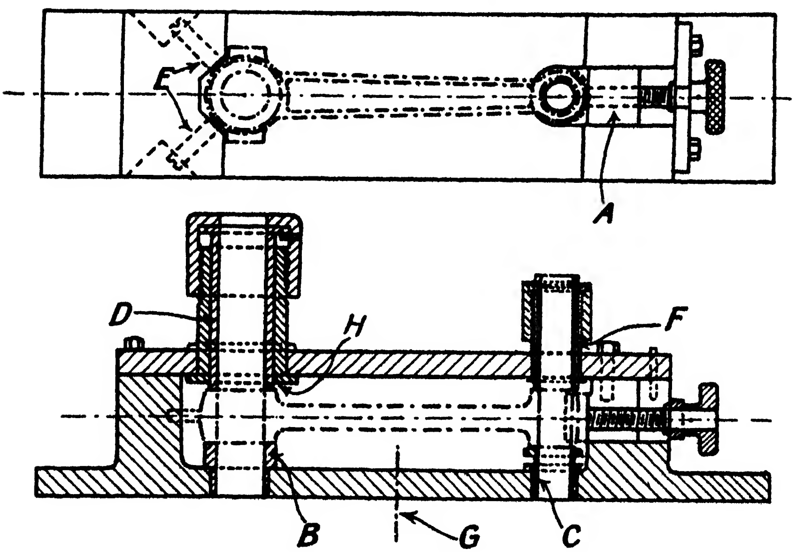


FIG. 85.

the upper bush F is brought down firmly. Guide bushings are inserted at D and F to suit the drill, boring tool or reamer to be used.

If many rods were to be machined with the aid of this jig it would be worth while to attach an indexing base so that the jig could be rotated about a central pin at G to bring each end in turn under the drilling spindle. This would speed up the operation considerably, but would not be essential for small sizes, at least.

This design illustrates several of the items which have been referred to in the general remarks about the location of repetition work. There is the location of rough surfaces by points at E and F, the location of finished faces by surfaces at B and H, and the introduction of supplementary supporting contacts after the position of the piece

has been fixed. Given reasonable care in the use of this jig the two holes should be bored parallel to each other. Once clamped the rod is not released until both holes are finished. Their relative positions depend on the large surfaces of the jig and not upon the very limited finished faces of the work. The principle may be applied to drill or

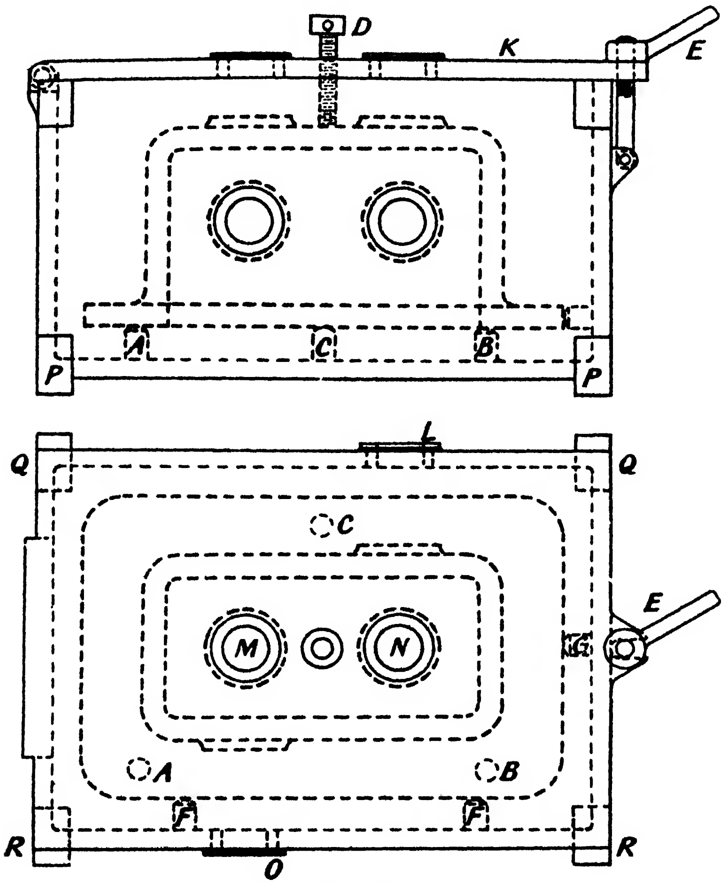


FIG. 86.

bore holes at given angles to each other, if the work be clamped in a jig having its external faces finished at the given angles. One application is drawn in Fig. 86.

In this figure the work is shown by the heavy dotted lines. It is placed in the jig and rests on three contact points, A, B and C. After the cover has been fixed in place by the clamp E, the work is held

firmly against the contact points, F, F and G. Thus it is definitely located by six contacts, and while so held it is clamped in position by tightening the screw D. Another screw placed so as to hold the work against the contacts F and F may be advisable if heavy drilling is to be done. The drill bushings carried at positions L, M, N and O should be long enough to guide the drills close up to the faces of the bosses to be drilled, otherwise the drills may wander out of line and the accuracy will not be good.

As will be seen from the figure, there are holes to be drilled into the sides of the work at right angles to M and N. For these holes bushes are fitted into the body of the jig. After drilling into the top of the work while the jig rests on the four feet P, the jig is turned so that it rests first on the feet P and Q and then on the feet P and R, which are machined square with the feet P. In the latter two positions the necessary holes are drilled in the sides of the work.

The above is an excellent example of the convenience arising from the use of a jig. The work is easily set in position by certain selected points. It is drilled in several directions and at selected points without any preparatory marking out. The relative positions of the various holes are fixed by means of the jig with a precision which could hardly be attained by any process of independent marking out and setting up. The difficulty of the latter method will be appreciated by consideration of the irregular shape of the work.

The hinged latch or lid is easily operated and is not located from the work, since the screw D is not tightened until nut E is locked in place.

When a casting or forging is to go through a series of operations and it is not possible or convenient to use the same fixture throughout, special locating faces should be machined upon it at the first operation. Without this precaution it will be impossible to ensure that the same contact faces shall be used in all the operations. If different contacts should be used, slight variations in thickness of metal or even irregularities of surface will affect the final shape of the machined work. Suppose, for example, a casting is to be planed on one face, A, and is later to be bored at two points, B and C, planing face A would naturally be the first operation. No other external face need be machined. The relative position of B and C is important, but they cannot conveniently be bored at one setting. For bore B the casting may be set flat on face A against three stop pins on adjacent rough faces. To hold the casting for finishing bore C, similar locating points in another jig might be used, but unless the points were

identically placed it is very unlikely that every one of a batch of castings would be machined interchangeably with all the others. There might be a small projection on one casting at a point near the locating contact in one jig, just where it would catch the contact point in the second jig. Many similar variations might occur, any one of which would displace one setting relatively to the other.

To avoid such risks, after planing face A the casting should be placed in a jig by reference to some important dimensions, for example, the thickness of metal to be left at some essential parts, and two holes should be drilled and reamed square with the planed face. Pins to fit the two reamed holes should be placed in every jig used in later operations. These pins, together with the planed surface A, would suffice to bring the castings into the correct position in all the jigs. The two holes should be separated as widely as possible. In this way slackness of fit on the pins, such as might arise from wear, will have less effect on the position of the work than if the holes were close together.

The method of location from a machined face and two reamed holes is adopted in the case of automobile cylinder block castings. The castings are milled on the lower face of the flange and certain other external surfaces depending on the design of the block. For this operation the castings are set with regard to the cylinders to ensure uniform metal thickness after boring. In the second operation two holes are drilled and reamed in the flange, while the part is located by the milled faces. All the subsequent boring, drilling and tapping operations are done while the block rests on the lower face of the flange in a position fixed by pins projecting into the holes. Successive locations in this way are hardly less certain than can be secured by the use of one jig throughout.

The question is sometimes asked—why are jigs made to such extremely fine tolerances? The answer is akin to that in regard to the need for extremely small tolerances in making gauges.

The jig controls one operation in, possibly, a series. The permissible tolerance on the product is composed of the sum of the variations, plus or minus, of the separate operations. Therefore, if a large proportion of the total be taken up by any particular operation of the series, all the other operations must be kept within correspondingly fine limits. It must be admitted that the production of a jig within fine limits is more expensive than if the limits were coarse. But the jig, once made, will serve for a great many parts on each of

which a saving may be made if the tolerances for other processes are wide rather than narrow. These savings will generally outweigh the extra cost of making the jig with great accuracy. In other words, any saving in making the jig will have to be paid for by the loss of effective tolerance on the work and the resultant greater cost of manufacture of each component. As in the parallel case of gauges, the matter resolves itself into a balancing of costs. Where many parts are to be made it usually pays to make the jig with very great accuracy, keeping the essential dimensions within limits much finer than those specified for the work.

CHAPTER VII

SPECIAL METHODS USED IN MAKING JIGS AND FIXTURES

In making gauges and jigs it is sometimes necessary to bore holes very nearly in exact positions. The permissible error in placing such holes may be of the order of two ten-thousandths of an inch. It is difficult to realise fully what such accuracy means, but the following statements may help to give some idea. The scribed lines used in ordinary marking out are not less than three-thousandths of an inch in width, usually they are wider.

Accuracy Required

A line only two-thousandths of an inch wide is hard to see with the naked eye, even on a carefully prepared metal surface and in a favourable light. The width of such a barely visible line is about ten times as great as the error permitted in the location of holes in high-grade tool work.

In work of this class the ordinary method of marking out and drilling through the centre of a scribed circle is not capable of ensuring the accuracy required. Even under the best conditions the probable error by this method is about three or four-thousandths of an inch. Tool-makers have therefore devised special methods for locating and boring holes within fine limits. This is a much more difficult task than, say, finishing a cylinder within a ten-thousandth of an inch of a given diameter. When finishing the cylinder, the required diameter may be approached gradually by successive cuts and the problem of eccentricity is not serious because the tools are external to the work and may therefore be rigid.

But when finishing a hole it is usually necessary to correct the eccentricity of the initial hole, and this must be done with a tool which is not really rigid. That is, the boring tool will deflect more or less according to the depth of cut. Hence a series of light cuts must be taken, each cut reducing the eccentricity so that by the time the required diameter is reached the position error will be within the tolerance permitted.

Evidently precision boring for jig work involves two separate

requirements, namely, (*a*) locating the work with reference to the axis of rotation, and (*b*) boring a hole of given diameter truly concentric with that axis. Either the work or the cutting tool may rotate. Both methods are used and produce equally good results.

Definition of Axis of Rotation

As previously mentioned, marking out in the usual way is not precise enough for jig work, and some better means of defining an axis is required. It should be such that definite measurements may be made from reference lines or surfaces forming part of the work, and it should then provide a ready means of setting with regard to the axis of rotation.

Use of Tool-makers' Buttons

The method in which the tool-makers' button is used was relied

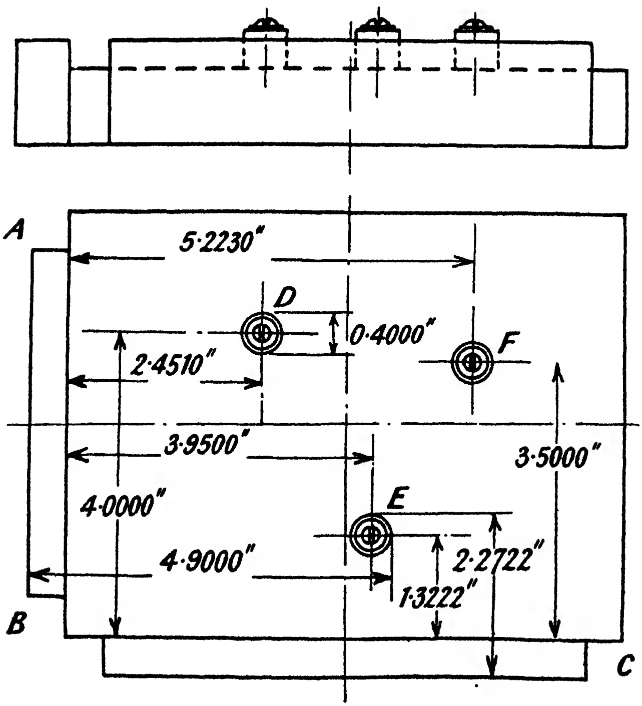


FIG. 87.

on for many years for the most accurate work and is still as precise as any later methods. It is, however, rather slow and is being

displaced by special machines where much work of the kind is to be done. The use of tool-makers' buttons will be understood from the following example.

Suppose holes are to be bored in a jig-plate, as shown in Fig. 87. The plate must be finished with its upper and lower surfaces plane and parallel, and the edges AB, BC must be squared up to serve as reference planes. Centres D, E and F must then be marked out, drilled and tapped, one-eighth inch in diameter. These centres need only be within a few thousandths of an inch of the given positions. They are merely for clamping the buttons to the plate.

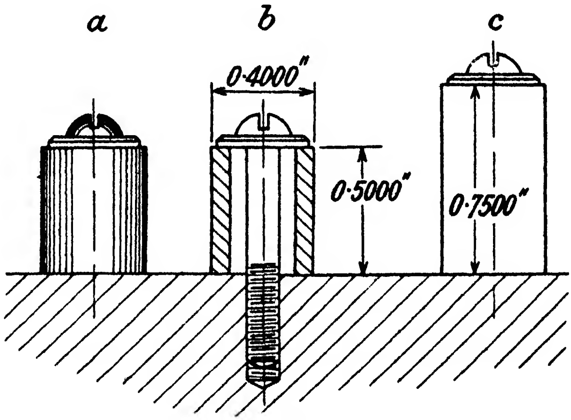


Fig. 88.

Parallel strips are next fastened to the edges AB and BC, so that they project about three-eighths of an inch above the upper surface. From these, micrometer measurements are made to the buttons.

Either an outside or an inside micrometer may be used, provided that additions or deductions be made to allow for the radii of the buttons and, in the former case, for the thickness of the parallel strips.

The buttons are shown to an enlarged scale in Fig. 88, *a* being an outside view and *b* a sectional view with the fixing screws in position; *c* is a long button for use when several are close together. They are made of hardened steel with the outer surface carefully ground to a suitable diameter (commonly 0·4000 inch), and both ends must be square with the axis. The bore is not of any great importance except that it must be large enough to allow ample clearance

round the fixing screw. This clearance is required to give latitude for setting the button correctly.

The plate having been prepared as described, and the three buttons being lightly screwed in approximate positions, they are tapped into place until their distances from AB and BC are right.

The screws are then tightened to hold them more firmly, after which the measurements should be checked over in case any movement should have occurred in tightening. When the centre-to-centre distance is important it is advisable to check this, as well as the distances from the edges of the plate.

The plate is now ready for the finish boring. For this it is clamped on the face plate of a lathe, care being first taken to ensure that the face plate is true, even to the extent of taking a light facing cut if necessary. The work is at first only lightly clamped, and it is adjusted until one of the buttons runs truly, as in Fig. 89. It is then finally clamped and retested to make sure that no displacement occurred in clamping. A sensitive indicator reading to a ten-thousandth of an inch is used for setting the work in position. Such an indicator is described on p. 81.

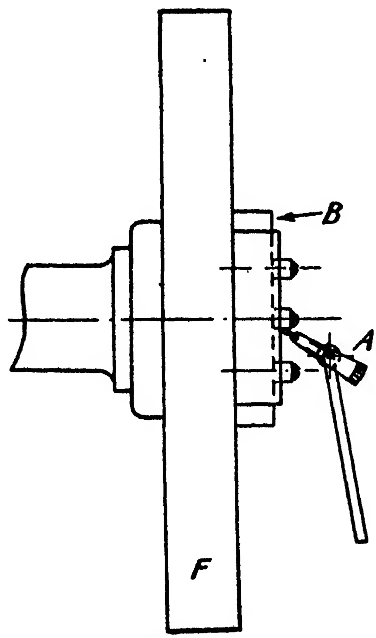


Fig. 89.

When the work is finally clamped and a button is running truly the button is removed. The original tapped hole is then enlarged with a short, stiff drill to permit the use of a single point boring tool. With this several cuts are taken, each reducing the initial eccentricity until the final bore runs truly with the axis defined by the button.

Balance weights should be used when the work itself is not in balance on the face plate, otherwise the varying forces set up vibrations, when running at anything but a very low speed, which will be great enough to spoil the accuracy of the work.

Setting by Gauge Blocks

As an alternative to the use of buttons the following method may be used. With care it is capable of almost equal accuracy, and if several holes are required it may save time.

Referring to Fig. 90, two parallel strips, A and B, are clamped on the face plate of a lathe, at right angles to each other.

These serve as reference planes or co-ordinates from which to locate the jig plate to be bored. If the distance of the bored holes from the edges of the plate is of consequence, the measurements, *a* and *b*,

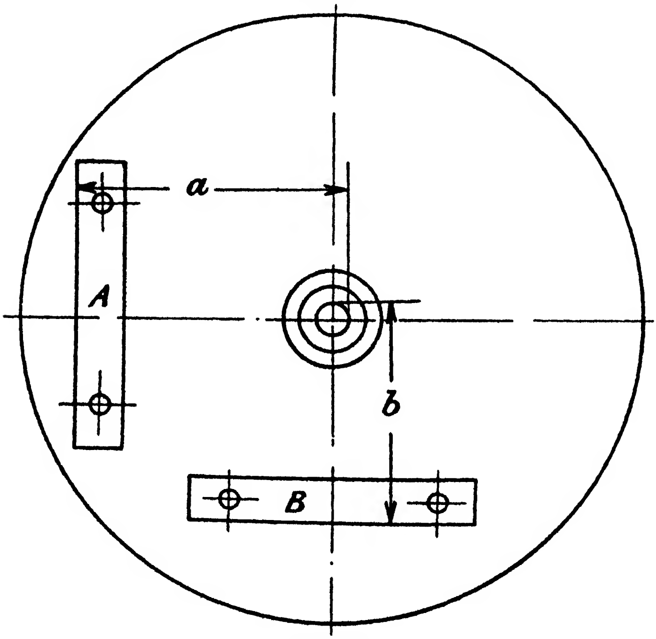


Fig. 90.

of the strips from the axis of the spindle must be known. To determine these measurements a soft steel plug may be fitted to the taper socket of the spindle and the projecting end turned in position, preferably to some definite and convenient dimension, as 1 inch.

When the positions of the strips are known it is a simple matter to set a jig plate from them by means of gauge blocks, as shown in Fig. 91, where B and C are the reference strips and A is the hole set from them. As before, care must be taken that the face plate and work are in running balance before any boring is done.

There is one advantage about the method in the actual machining,

which is that no preliminary hole is made in the plate, and there need therefore be little eccentricity to correct if a short stiff drill is used to spot the position before the actual drilling with a twist drill. This preliminary spotting will provide a starting point for the twist drill truly in line with the machine and will check the liability of the twist drill to start untruly.

A twist drill is not rigid enough to correct a fault in starting, and usually is deflected more and more as it feeds into the work.

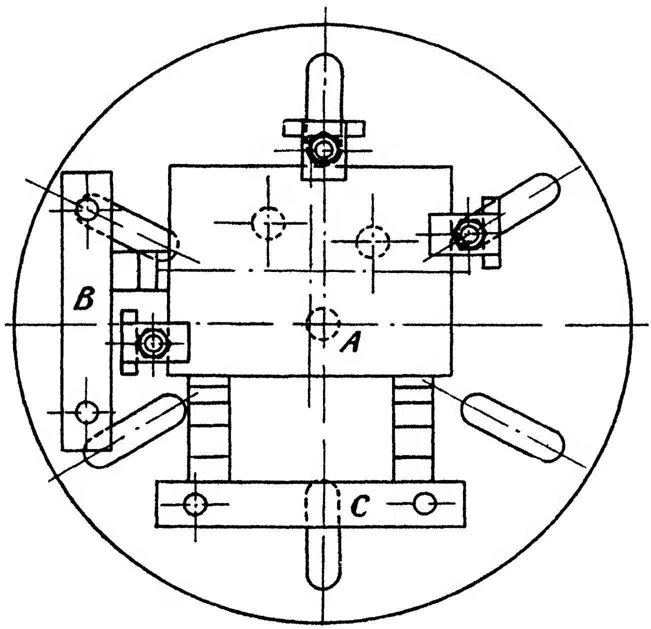


FIG. 91.

Use of Discs for Location of Holes

A development of the button method of locating and boring holes sometimes used in small work, is known as the disc method. The discs are turned of suitable diameters, so that when placed on the plate to be bored with their edges in contact their centres will be spaced at the required distances. It is possible that this method was originated in the watch and clock factories, since the spacing of pivot holes for gears would be likely to suggest the use of discs of diameters equal to the pitch diameters of toothed wheels in mesh. Whether originated there or not, the method has been much used in tool-making for watch and clock manufacture.

Discs are turned to the specified or calculated diameters, and, as each disc is turned, a small conical hole or small cylindrical projection is turned at the centre so that it will be concentric with the outer edge. This hole or projection is used with the aid of a sensitive indicator to set the disc concentric with the lathe axis. Fig. 92 shows one of the discs. These are usually cemented in position by means of shellac on the plate to be bored. The plate with discs attached is then mounted on a face-plate and each disc is used in turn to set the work in line with the lathe axis. After a disc is set truly central for the boring operation, it is detached and the work is drilled and bored. It is possible to avoid the removal of the discs if they are made with a sufficiently large central hole to allow the boring tool to pass. This hole must be bored concentrically when the outer

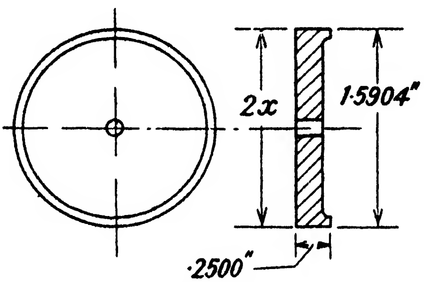


Fig. 92.

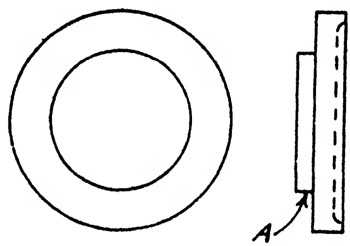


Fig. 93.

diameter of the disc is turned, so that it may be used as the centring surface. Alternatively the disc shown in Fig. 93 may be used, with the outer edge of the central projection A as the setting surface, but a disc of this form must of course be removed from the work previous to the boring operation.

An example showing the use of the method is shown in Fig. 94.

The original dimensions may be given as centre distances or from perpendicular base lines. In the work to which the discs are usually applied the centre distances are likely to be the essential dimensions, and it is therefore advisable to use them as a basis. Starting with the rectangular co-ordinates, as given in Fig. 94a, the centre distances are found as below :

$$AB=\sqrt{0{\cdot}4419^2+1{\cdot}8103^2}=1{\cdot}86347 \text{ inches.}$$
$$BC=\sqrt{1{\cdot}0181^2+1{\cdot}7103^2}=1{\cdot}99048 \quad ,,$$
$$AC=\sqrt{0{\cdot}1000^2+1{\cdot}4600^2}=1{\cdot}46345 \quad ,,$$

From the centre distances the radii of the discs are next calculated—

$$AB=z+y,\ AC=z+x,\ BC=x+y,$$

whence, $x=0{\cdot}7952''$, $y=1{\cdot}1952''$, $z=0{\cdot}6682''$.

Hence the diameters of the three discs are 1·5904 inches, 2·3904 inches and 1·3364 inches.

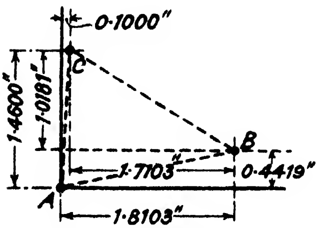


FIG. 94a.

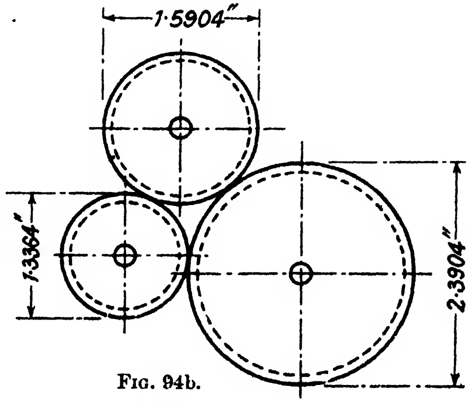


FIG. 94b.

Knowing these dimensions the discs are carefully turned to size, the centre hole or projection being turned at the same setting as the outside diameter.

As a rule the method is used for small work for which buttons are not convenient. The example is rather larger than most of the work done in this way. Several very useful variations of the disc method have been devised. For example, more than one set of centres may start from a common point as in a train of compound gearing. In a case of that kind stepped discs of two or more diameters will enable both sets to be laid out at once. Thus the trouble of fitting plugs to holes, which are already bored, may be avoided. The diameters of the stepped discs for a clock motion jig plate could be made equal to the pitch diameters of the wheels and pinions intended to mesh. The discs should be made with a sufficiently large central hole to permit the boring to be done through them without detachment.

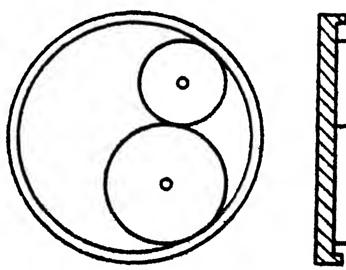


FIG. 95.

It does sometimes happen that holes are to be spaced on a circular

plate on which it is not possible to use a central disc. A raised edge or flange of suitable internal diameter may then be turned on the plate as shown in Fig. 95, against which the discs may be placed in contact. If not afterwards required the projecting rim may be turned off.

Location from Centre Dots

The button or disc method of location for boring is tedious, and several methods of accurate location have been devised in order to reduce the expenditure of time. Some of these alternative plans save time without any sacrifice of precision. These involve the use of expensive machines or fixtures and are described later in this chapter. There is, however, one method which will give results nearly as good as may be attained by the buttons in considerably less time and with relatively inexpensive appliances. Briefly, the method depends on careful centre dotting at the intersections of marking out lines. The centre dots so placed are then used to receive the point of a special indicator, with the aid of which each dot may be set in line with the axis of a lathe spindle. When this has been done the hole is drilled and bored as already described in connection with the disc method of location. This part of the process should introduce but little error if done with care. But if the final result is to approach the accuracy of the button or disc method, there are certain precautions which must be taken in setting out and centre dotting the centres. In the first place the marking out must be done by some means which will enable the lines to be drawn within plus or minus one ten-thousandth of an inch of the specified position. This can be done most readily by means of Johansson blocks and the special surface gauge base described on p. 51, Fig. 28. Secondly, the marking out lines should be of a symmetrical vee form in cross-section, which may easily be ensured by sharpening the scriber point correctly. The symmetrical form of vee will give correct centring independently of the depth of the mark (see Figs. 37 and 38). The last stage in the marking out is to centre dot the intersections of the marking lines. To do this with the precision needed a special punch is required (Fig. 33). This punch slides in a holder mounted on three guide points whereby it is held perpendicularly to the marked-out surface and at the same time located in the correct position. Two of the points, A and B, lie in the same straight line as the punch C, which is midway between them. These two points are placed in one of the marking lines, and the holder is then moved along that line until the third point D is felt to drop into the other marking line at right

angles to the first. The punch will then be over the intersection of the two lines and a light tap will mark the required point. It is advisable to keep this punch solely for light preliminary marking and to use a second one to deepen the impression. The punches and supporting points should be ground in a tool or universal grinding machine with conical points of 60° included angle truly concentric with the shanks. Free-hand grinding will not do. The scriber points used for marking out should be of 50° to 55° angle. The punch will thus be located by the edges of the line, more certainly than if th supports were more sharply pointed, and so reached the bottom the line (see Fig. 96). A test bar for use with an indicator for centring the marks is shown on p. 82, Figs. 72 and 73.

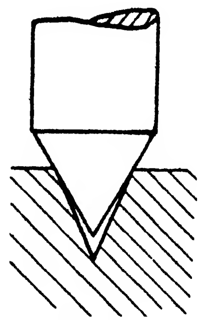


Fig. 96.

A large proportion of the time occupied in jig-boring by either the disc or the button method is taken up in the initial setting of the discs or buttons on the work, that is, in defining the axes of rotation for boring the holes. It is therefore in this part of the work that there are the greatest possibilities of time saving. The use of two perpendicular reference planes fixed to a face plate in conjunction with gauge blocks has already been described. It is capable of saving a part of the time, but it involves unfastening and reclamping of the work.

A neater method, saving still more time because the work need not be released, is to use two perpendicular slides carrying a tee-slotted table upon which the work may be fastened. With the aid of an accurate measuring device these slides may be used to set the work quickly in definite positions in relation to the two base lines. Beginning with any known position of the axis of rotation it is easy to displace the work rapidly and definitely to other positions, and there is no need actually to mark out the work or to set discs or buttons to define the required axes.

Application of Compound Slide Rest for Location of Bored Holes

Various methods of measuring the displacement of the slides are in use. In one of them gauge blocks of the Johansson type are placed between a fixed contact on the stationary member and the contact face of a dial gauge attached to the sliding member. The dial gauge may be used simply as a contact pressure indicator by

setting the sliding member always to give the same reading on the gauge. This method involves the building up of the required dimen-

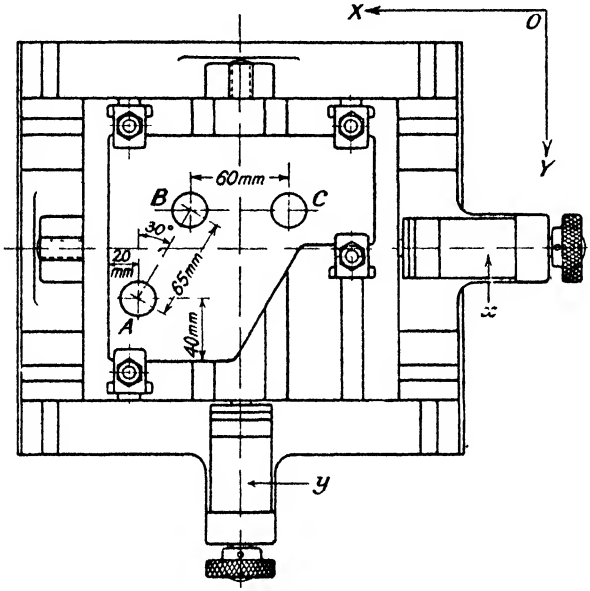


FIG. 97.

sions completely with gauge blocks. But good class dial gauges are made of sufficiently high quality to justify their use as a supplement to the gauge blocks in order to add small differences to the main dimension given by the gauge blocks.

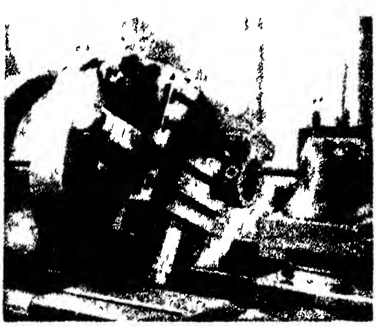


FIG. 98.

This is a more rapid method, and provided the dial gauge is checked from time to time is no less exact. It will be noticed that screws are used to move the slides, but as these screws are not used for measuring their accuracy is of no importance. Fig. 97 shows a pair of slides made by the Johansson Company, with gauge blocks at x and y, for the application of this method. These slides may be mounted on the face plate of a lathe, as shown in Fig. 98, and the

boring finished by a single point tool after drilling, or they may be used on the table of a drilling or vertical milling machine.

As the demand for very fine tool-making has grown, attention has been turned to even more effective means of production. Special jig-boring machines have been built, which depend upon the principle just described, that is. upon definitely measured displacements of the work, which is not unclamped until finished.

Jig-boring Machines

These machines embody the two essential slides, together with a high-class boring spindle with axial feed motion. The whole of such a machine must be built with great rigidity and the utmost accuracy to ensure the precision which is asked. Given these essentials, which are necessarily costly, the machine enables one man to turn out as much work of the highest quality as could be done in the same time by several tool-makers working by the older methods.

The methods provided for measuring the displacements of the slides differ in various makes. The feed screw with micrometer dial commonly used in ordinary machine tools is not adequate when tolerances of one or two ten-thousandths of an inch are needed. Even if it were initially good enough, unequal wear would cause irregularities and the original quality would be lost.

There are two methods of obtaining and maintaining the essential precision. In one, the feed screw is made of very generous proportions and the frictional resistance of the slides is reduced to the minimum compatible with stability. In the other method, the means of measurement is entirely separated from the screws which are used for the feed motions.

The former plan is adopted by the Société Genevoise in their jig-boring machine, which is shown in Fig. 99. In general outline this machine resembles a planing machine, but the cross-rail carries a vertical boring spindle instead of a tool-box. Large vertical movements of the boring spindle are made by raising or lowering the cross-rail. Such movements are intended to accommodate different sizes of work, and are controlled by two accurate screws, one at each side, which ensure that the cross-rail remains parallel to the table in all positions. For feeding the tool the spindle is carried in a long sleeve having a vertical sliding motion.

The work which is to be bored is mounted on the machine table. Any point within the range of the machine may be reached by the

use of the longitudinal slide carrying the work-table and the cross-slide carrying the boring head. The tool is provided with a vertical feed motion. Carefully cut guide screws are used for both the longitudinal and cross-feed motions, but no attempt is made to have these

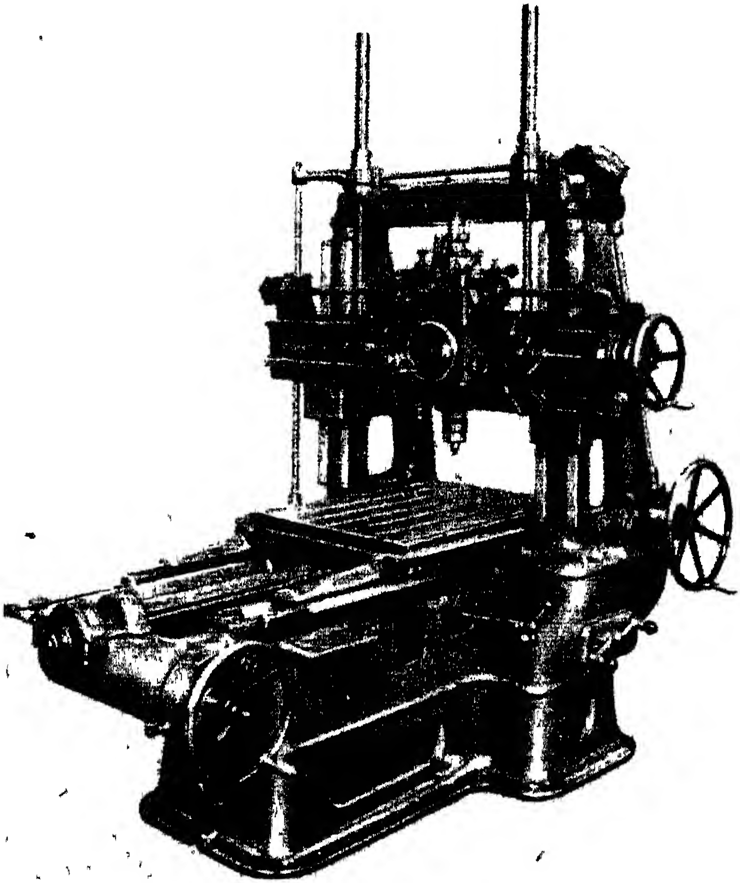


FIG. 99.

screws correct in pitch within one ten-thousandth of an inch, which is the guaranteed accuracy of the machine. Such accuracy would be needlessly expensive, even if it were possible. It would also have the disadvantage that new screws would be required if uneven wear should occur, which is always a possibility. To avoid the use of

such costly screws the mechanism shown in Fig. 100 is used. The screws are cut within narrow but reasonable limits of error. They are then calibrated, and the variations from true pitch are tabulated and a correction plate is made. This plate is a strip of steel shown at A, equal in length to the movement of the slide.

One edge of this plate is formed to an undulating contour, so that the transverse dimensions of the plate are proportional to the pitch variations already tabulated. The plate is then attached to the sliding member so that it may act through a rocking arm B on a piece C, which carries the zero line for the micrometer dial D.

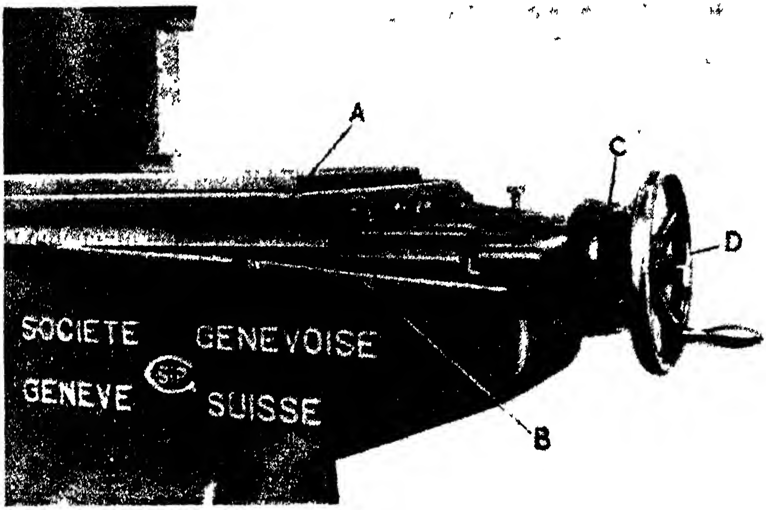


FIG. 100.

The effect of the arrangement is therefore to move the zero mark backwards or forwards as the pitch of the lead screw is long or short. For example, if at one part of the screw the pitch is slightly long, the contour of that part of the plate which comes into action is such as to bring the zero mark towards the required micrometer setting. Thus the actual motion of the screw is slightly reduced, and the pitch error is automatically corrected. If there should be cause to suspect unequal wear, it is not necessary to have a new screw made. The initial accuracy of the machine can be restored by a recalibration of the screw and alteration of the contour of the correcting plate or the replacement of the plate with a new one. Either alternative is much less costly than a new screw.

The work of the lead screw is made easy by the construction of the slides of the carriage and table. These are not made continuous but are made in equally spaced sections. Thus the lubrication is made more perfect. The sliding surfaces are lapped to produce the final working surface. These very perfect surfaces adequately lubricated move very easily and are subject to very little wear. Also the work done by the screw in moving the slide is so slight that it shows no appreciable wear even in years of use.

Guards are fitted to keep the slides free of cuttings and dirt.

To lock the sliding head in position when boring, there is a secondary nut which may be given an axial motion relative to the main nut, thereby holding the slide definitely up to one face of the screw. The work-table is fitted with a similar arrangement. Both the sliding head and the work-table may be locked to their guides by a clamp which ensures rigidity when boring, and is designed to exert no force tending to move the table as it is tightened.

The Société Genevoise has recently (1934) built a jig-boring machine which is entirely independent of screws for the accuracy of its settings. A scale very precisely graduated in tenths of an inch is attached to each moving member, namely, the table and the boring head. To the corresponding stationary parts are attached microscopes with cross-webs, conveniently placed for observing the scales. The cross-webs are double, one part being fixed and the other being movable through rather more than one-tenth of an inch by means of a micrometer reading in tenths of a thousandth of an inch. Thus it is possible to set the table or the boring head to the nearest tenth of an inch by the scale and to subdivide this by the movable cross-web. The general arrangement of the new machine is very similar to the screw-operated pattern shown above, but the method of moving the table is different. A hydraulic feed mechanism is fitted and provides a rapid motion for rough setting and a very fine adjustment for the final setting. The change from one to the other rate is quickly made, and the hydraulic feed no doubt contributes considerably to the speed which is claimed for this machine. Another factor tending to increase the speed of operation is the elimination of backlash from the method of placing the moving parts. If the scales show the required reading in the microscopes, it does not matter which side it has been approached from, it will be equally correct. When screws are relied upon for measurement, on the contrary, it is essential to approach the desired position always from one direction, otherwise there will

be an error equal to the backlash of the screw. In the machine under consideration the hydraulic motion is applied to the table only. The boring head is moved by an electric motor acting through a screw, but since the screw is not used for measurement, the backlash does not affect the position of the head, which is read directly from the scale and microscope device. The scale method of measurement avoids deterioration through wear and makes it possible to use the machine for milling operations without risk of impairing its accuracy. In the older pattern, using the screws for measurement, excessive use for feeding purposes was to be avoided.

The jig-boring machine just described is of especial interest because it illustrates a growing tendency to introduce optical methods into machine shop operations. There is little doubt that as these methods become better known they will be adopted much more widely in the future.

The Pratt and Whitney jig-boring machine has the general form of a vertical spindle milling machine. The spindle is vertically adjustable above two horizontal slides at right angles to each other. These slides are well supported on an integral part of the main frame casting of the machine. On the uppermost of these slides there is carried the tee-slotted work-table. The construction of the whole machine is exceedingly substantial and the design is such as to preserve the initial accuracy of the machine for a long period. For instance, the sliding surfaces are of ample area and are fitted with felt pads and oilers which keep them clean and lubricated.

The measuring device is entirely separate from the screws which move the slides. It is not subject to wear, and it may be checked very easily at any time. Referring to Fig. 101, which shows the lower slide and its setting device, a hard steel contact piece is to be seen on the sliding member. Opposite to this on the fixed part of the machine a dial gauge is mounted. Between the dial gauge and the contact face a vee groove is machined. Cylindrical end blocks, shown separately in Fig. 102, are placed end to end in the groove to make up whole inch distances. For subdivisions of the inch these are supplemented by a robust inside micrometer graduated to tenths of a thousandth of an inch (Fig. 103).

As an example of the use of the machine, suppose that, one hole having been bored, it is required to move the slide 3·3012 inches nearer to the column of the machine. It is assumed that the blocks and the micrometer are already in place for the original setting, and

that the dial gauge indicates +5. The micrometer must be reset to a reading 0·3012 inch greater than the initial value. Also a 3-inch gauge block must be inserted in the line of blocks. The slide must

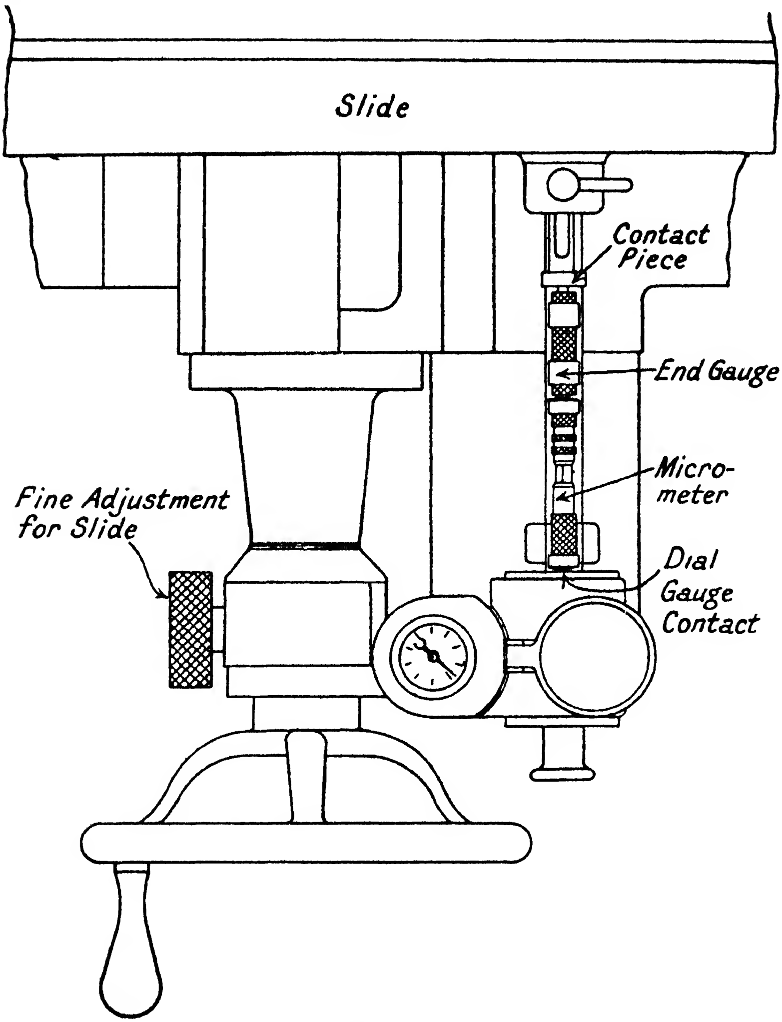


FIG. 101.

therefore be moved inwards rather more than 3·3012 inches to make room between the fixed stop and the dial gauge for the lengthened micrometer plus the 3-inch gauge block in the groove.

These having been inserted, the slide is brought back until the

dial gauge again indicates +5. Although the dial gauge is not used directly as a means of measurement, it is a very important item in the method, as any one who has tried to set a slide with extreme accuracy to a dead stop will realise. No matter how rigidly a machine may be built, spring or deflection cannot be entirely avoided. The extent of the deflection will depend upon the force applied in bringing the slide up to the stop. But if the dial gauge is used there is no need to estimate the contact pressure in the hope of keeping it equal in all settings.

The gauge indicates the position of the slide on a very greatly

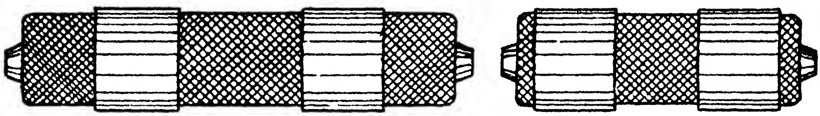


Fig. 102.

magnified scale, and the pressure required to operate it is far too small to cause any deflection in the machine. The case is analogous to that of measuring machines, in which certainty of measurement within the thousandth of an inch can only be ensured by the use of constant contact pressure.

After the slide has been set in the required position it is advisable to lock it in position before beginning to bore. Here the dial gauge

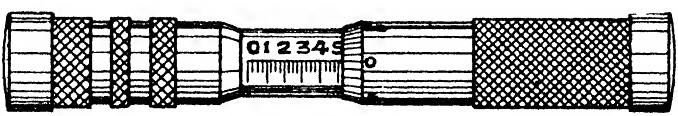


Fig. 103.

performs another useful function. If the slide should move during the act of clamping the dial gauge will immediately indicate the motion.

Methods of Boring Truly with Axis of Rotation

So far we have been occupied principally with the problems of locating a piece of work definitely in position with reference to a fixed line, that is, with reference to the axis of the machine spindle. There still remains to be discussed the related problem of how to bore a straight hole truly concentric with the chosen axis. This requires in the first place a carefully fitted, truly running spindle.

The hole is usually drilled in the first place with an ordinary twist drill. This first hole must be well below the finished size, because it is most unlikely that it will be concentric throughout with the specified axis. Any one of several causes may contribute to this eccentricity. For instance, the point of the drill may be slightly off the axis of rotation so that the hole will be started out of line, in which case it will become worse as it goes deeper; or the material to be drilled may be uneven in density and deflect the drill. It should be remem-

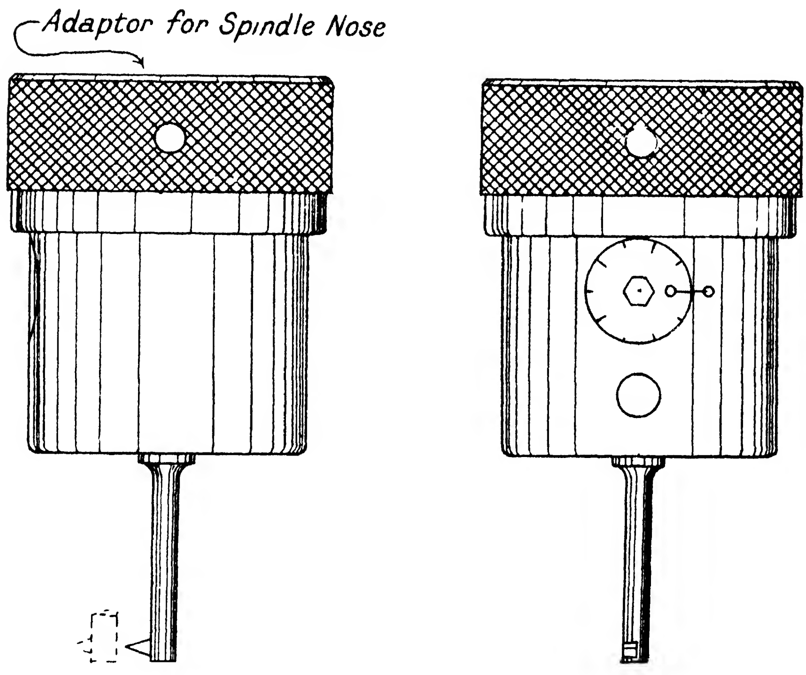


Fig. 104.

bered that a twist drill is not a rigid tool, and that it may be quite easily deflected by a hard spot, acting on the inclined cutting edges and so setting up a lateral pressure.

To enlarge the hole to the required size and at the same time to rectify any eccentricity two methods are available. The first is to take a series of light boring cuts with a single point tool. Each cut brings the hole more truly into position, until finally the error is within the tolerance permitted. A tool-holder and tool, made by the Pratt and Whitney Co. for this purpose, is shown in Fig. 104. It

will be seen that a means of adjustment is provided so that by its use a hole may be conveniently enlarged to a given size. An alternative method depends on the use of an end mill as a boring tool. A single cut with such a tool is usually sufficient to bring the original drilled hole concentric with the required axis.

The cutter is relatively stiff, being of the full diameter of the hole. Also the cutting edges are perpendicular to the axis and therefore variations in the depth of cut can give rise to little or no lateral pressure to deflect the tool. The objection to this method is the difficulty of keeping within fine diameter tolerances, since the cutter must bore a hole larger than its own diameter unless it is running with perfect concentricity. If the initial hole is not drilled very near to the correct position it is advisable to begin the precision boring with an end mill well under the desired diameter and to follow it with other end mills of successively greater diameters. In this way the eccentricity of the original hole is gradually corrected until by the time the full diameter is almost reached the hole will lie truly in the specified position. This method is obviously little, or no, faster than boring with successive cuts by a single point tool. When the hole is correctly bored by the end mills it may be finally brought to size by a reamer, but it must be remembered that a reamer will follow the existing hole and will not assist to correct its location.

Value and Limitations of Polar Co-ordinates

When work is of a form most easily dimensioned in polar co-ordinates, that is, when the centres are shown by distances measured along radial lines specified by angles from a given line passing through the centre of measurement, then a circular dividing table may be used with advantage. But the question of accuracy must be kept in mind, otherwise the work may be of a lower standard than is expected. For example, a circular table which may be relied upon to be accurate to five seconds is exceptionally good. If this table is 2 feet in diameter and is used for spacing holes at the full diameter, the possible error is nearly three ten-thousandths of an inch, which might easily be too great. The error would of course diminish with the radius, and within 4 inches radius would be less than one ten-thousandth of an inch. Where the maximum accuracy is required the dimensions should be translated into rectangular co-ordinates. The calculation of a typical case is shown below.

The points A, B and C are dimensioned on the drawing by radial

and angular measurements from the intersection of YY and XX and from the base line XX. Unless there is an unusually accurate rotary table, it will be better to work entirely by dimensions from the two lines XX and YY. To find a_1 and a_2—

$$a_1 = 3{\cdot}0000 \times \cos 30° = 3{\cdot}0000 \times 0{\cdot}86603 = 2{\cdot}5981''$$

$$a_2 = 3{\cdot}0000 \times \sin 30° = 3{\cdot}0000 \times 0{\cdot}50000 = 1{\cdot}5000''$$

To find b_1 and b_2 —

$$b_1 = 14{\cdot}150 \times \cos 70° = 14{\cdot}150 \times 0{\cdot}34202 = 4{\cdot}8395''$$

$$b_2 = 14{\cdot}150 \times \sin 70° = 14{\cdot}150 \times 0{\cdot}93969 = 13{\cdot}2966''$$

and so on.

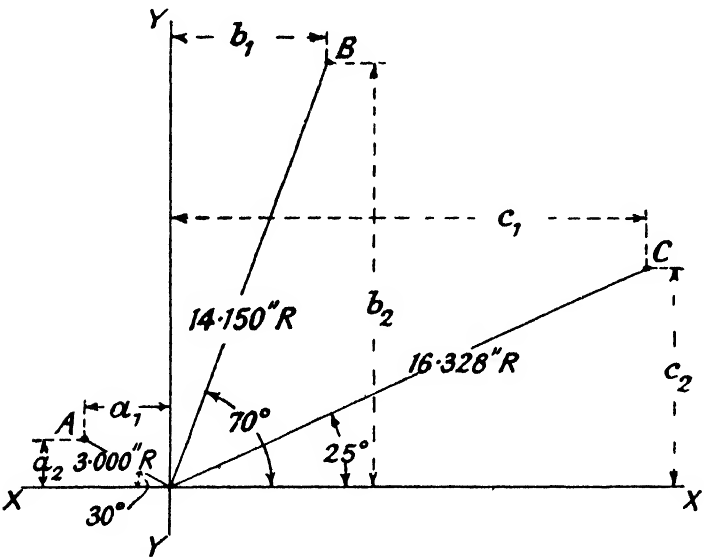


FIG. 105.

Determination of Position of Axis of Spindle from Edge of Work

When boring jigs or other accurate work it may be necessary to find out exactly how far the centre line of the boring spindle is from the edges of the work or jig plate. One method of doing this has already been described in connection with the use of tool-makers' buttons on p. 108.

Another very useful method is to insert a steel plug in the spindle nose or chuck and to turn the projecting end of this plug very carefully so that it is a true cylinder. The diameter is immaterial but should be measured. A height gauge is used to measure the height of the specified edge from the machine table. To this measurement

is added half the diameter of the turned plug and the height gauge is reset to this new height. Finally, the spindle is set vertically to a height from the machine table such that the gauge just makes contact with the top of the plug. The method is illustrated in Fig. 106a.

An indicator attached to the height gauge will make it easier to

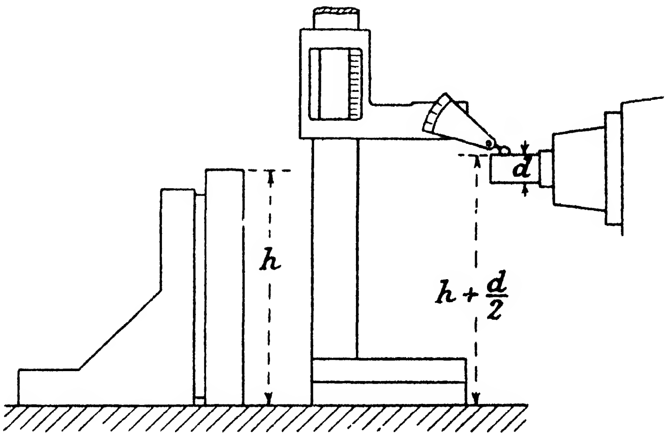


Fig. 106a.

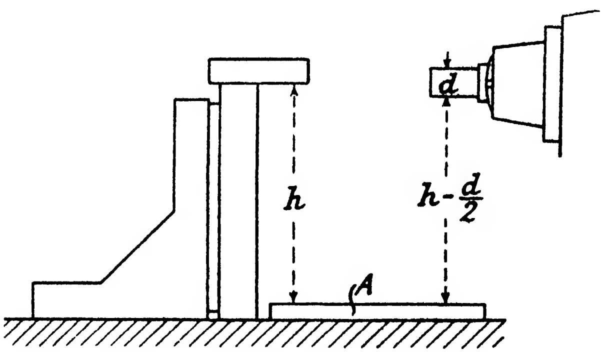


Fig. 106b.

read the position of contact. Care should be taken to work always to the same scale mark on the indicator throughout a series of measurements.

As an alternative to the height gauge, an inside micrometer may be used to measure the distance between the plug and the table. This method may introduce errors on account of the existence of bruises or indentations in the surface of the table, but the use of a parallel

steel plate A, as shown in Fig. 106b, will obviate such faults, so long as no burrs are left standing above the general level of the table.

For locating the spindle horizontally with regard to the edge of the work a parallel strip A may be used, as shown in plan in Fig. 107. The strip is clamped to the work and provides a surface from which measurements may be made with a micrometer to the plug. In Fig. 107 an outside measurement is shown, but an inside micrometer may be more convenient in some circumstances.

Cases may arise in which it is not convenient to attach a parallel strip directly to the work. For example, there may be no planed surface of suitable position or extent. An accurate angle plate bolted to the table with one face vertical and parallel to the machine spindle will simplify the work in such cases. The vertical face will

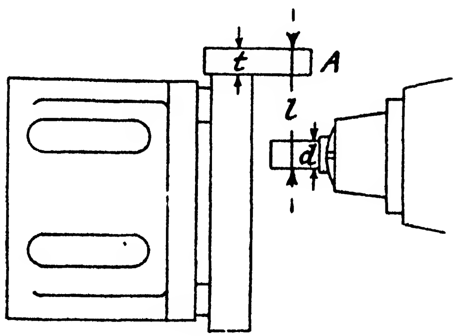


Fig. 107.

provide a common surface from which the distances of the spindle and of any important point of the work may be measured.

Trouble may be saved by using a boring tool holder which has part of the projecting shank ground true with the axis of the machine spindle. This may be used instead of a separate plug and will obviate the frequent changing of plug for tool when many holes have to be located and bored. A boring tool holder with adjustable cutter is shown in Fig. 104. A fixed part of the holder may be ground true and will be convenient for setting.

The button method of locating holes, as described in the earlier part of this chapter for use when the work rotates on a face plate, may be adapted to the boring or milling machine. The rotating spindle presents a difficulty because the indicator used for aligning the button must rotate with the spindle, and it is not easy to see in

all positions as the spindle turns. A mirror is helpful, but the observations are still troublesome. As a substitute for the indicator, a sliding sleeve, closely fitted to a turned plug of the same size as the button, will give good results if used with care, although hardly as precise as the indicator. The sleeve should be of fair length and should fit both the plug and the button separately without perceptible shake. The position of the work is adjusted until the sleeve will easily slide on to the button, while still remaining partly on the plug.

The value of a base plate to which a piece of work may be attached during a series of machining operations is referred to in connection with boring machines in Chapter VIII. The base plate is very useful also when machining irregularly shaped parts having no external surfaces of considerable extent which need to be machined. It may be necessary to bore or otherwise finish internal surfaces on such parts. The relative positions and angles of the finished surfaces may have to satisfy very precise specifications. Attachment to a base which need not be removed throughout the machining will enable settings to be made with ease and precision. The part should be attached to the base so that the principal machined surface is definitely located parallel to the base surface and to one side of it. The outside of the part should be placed in such a position that the finished thicknesses of metal will be satisfactory. After machining one surface the part may be reset for the second operation by moving the base and the part as a unit. The advantage gained is that comparatively large surfaces are available for obtaining alignments and angular settings. Figs. 112 and 113, Chapter VIII, show how the method is used.

When working to narrow limits the effect of spring or deflection becomes very important. For, even when relying upon a dead stop to limit a transverse motion, a difference in the force applied may be quite enough to vary the extreme position of the tool slide by a distance approaching 0·001 inch. In jig-boring machines where distance blocks are used to define positions the difficulty is met by the use of an indicator which is brought to zero for each setting. Used in this way, the indicator is really a spring balance showing contact pressures, which may thereby be kept to a constant value. The repetition of size in hand-operated machines, e.g. turret or capstan lathes, is dependent on the ability of the operator to apply the same pressure each time he brings the tool slides up to the stops which control diameters or lengths. The closeness of repetition depends

upon the skill of the operator and an experienced man should be able to maintain tolerances of 0·001. But as tolerances are decreased a time comes when the operator's judgment no longer suffices to repeat settings with the necessary precision. Then the replacement of the solid stop with a dial gauge will permit work to be produced within tolerances of one-half thousandth of an inch. The gauge is mounted on the fixed member of the slide and a stop on the moving member so that at the required depth of cut or length of traverse the gauge will indicate some constant reading. A useful extension of the method is to provide for the interposition of length gauges between the gauge and the stop. By this means it is possible to turn a number of diameters or lengths by the use of suitable gauges or distance pieces. Dial gauges graduated to 0·0001 inch are preferred as they are easy to read and so minimise the risk of error.

Another method of ensuring constant pressure is to introduce a slipping clutch in the feed drive. This is very effective, although of less delicacy than the indicator. Irregular contact pressures and unequal cutting forces are always a source of trouble in precise dividing or indexing operations. Very often when all possible care has been taken in machining it is still necessary to make a final adjustment by hand.

This is especially necessary when work of large diameter is to be divided accurately. An example is given below, where the method of finishing the indexing mechanism of the Bullard Mult-au-Matic is briefly described.

The part concerned is known as the carrier, which holds the work spindles. Its diameter is about 5 feet 8 inches. The function of the carrier is to bring the revolving work spindles each in turn opposite the tool slides. Any error in position of the work with reference to the tool slides will directly affect the diameter of the work turned or bored. The indexing of the carrier must therefore be done very accurately. It is in practice limited to an error not exceeding plus or minus one-thousandth of an inch at the circumference of the carrier.

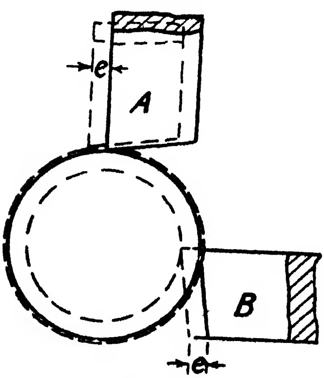


Fig. 108.

In passing it should be noticed that errors in diameter arising from faulty

indexing in machines of this type are least when the tool is presented to the work in position A, Fig. 108, rather than position B. It is clear from the diagram that quite a serious error, *e*, in position will have but little effect on the diameter of the work at A, whereas at B the diameter of the work will be affected to the extent of twice the error in indexing.

That part of the machine which is known as the carrier supports the rotating work spindles and must be turned periodically through an angle of 60° to bring each work spindle in turn opposite the tools. The diameter of the carrier is nearly 6 feet, and the permitted error in locating the work is $\pm 0{\cdot}001$ inch. For so large a piece this is an extremely small variation.

The carrier is mounted on its own bearing on a special stud in the boring machine. There are six radial holes to be bored equidistantly round the circumference. The preliminary boring of the six radial holes is done by means of a core drill and a boring bar with two cutters. After boring one hole the carrier is indexed to bring the next into position by means of an indexing pin set at 60° to the boring spindle. This pin engages with the hole just bored. The top and bottom surfaces of the carrier are now finished while it is mounted on its own bearing. Next, six holes are drilled in the top face of the carrier with the aid of a jig which is located in the radial holes already bored. The six holes in the top face are used for the attachment of the special adjustable buttons as shown in Fig. 109.

These buttons are made with a slightly flexible shank, A, so that the screws B and C may be used to move the head of the button either radially or tangentially. The adjustment is very small and the tilt of the button on that account is too small to be perceptible. Using the radial adjustment, all the buttons are set concentrically with the axis of the carrier. A dial gauge supported

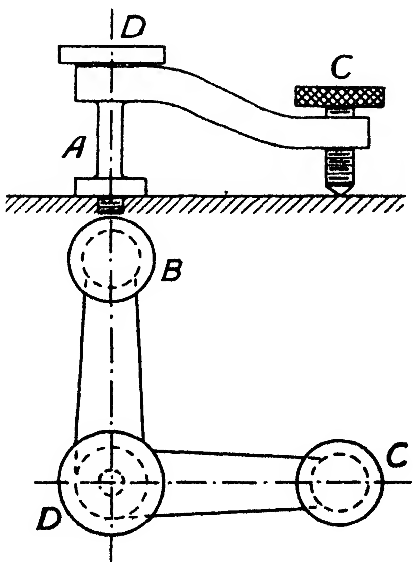


Fig. 109.

by a bracket from the stud on which the carrier rotates is employed for this setting. The other adjusting screws are then used to set all the buttons equidistantly by means of a chordal gauge reading to 0·0005 inch. In each of the radial holes of the carrier is inserted a plug having a notch A, Fig. 110, across the end, for the index pin B to engage with. The index pin is carried in a socket in the tool post. When the carrier is set up with the indexing mechanism assembled, it is rotated into the six working positions, and the adjustable buttons are indicated by a dial gauge. Owing to the difficulty of locating so large a part with certainty and the liability of the boring tools to run, it is likely that the dial gauge will not give the same reading for each button. The variations in the readings indicate faults in boring the holes to contain the index plugs. They are rectified by stoning the faces A or B, which make contact with the pin.

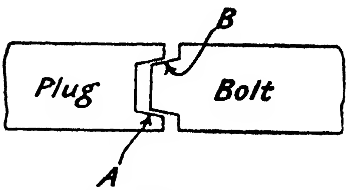


Fig. 110.

When the carrier is made to index within the specified limits the spindles are set by trial in the correct positions. The method of attachment of the spindle bearings by a flange to the carrier is designed to permit a small variation in position. After the setting is correct three dowel holes are drilled in each flange and pins are fitted. A very full description of the work outlined above is given in the "American Machinist," vol. lxvi, p. 725.

CHAPTER VIII

METHODS OF MACHINING TWO OR MORE SURFACES IN SPECIFIED RELATIONSHIP

In many cases it is desirable to complete the machining of a piece without reclamping it. There are several advantages gained by this. For example, some pieces are of such shape that much trouble is required to clamp them securely and without distortion. This care having been taken once, time is saved and risk of error is diminished if resetting and reclamping can be avoided. This is one of the valuable features of jigs whereby holes may be drilled from several directions by using surfaces on the outside of the jig to determine its position with regard to the axis of the drill. In some applications of the principle it may happen that settings after the first one may be much more accurately done because the piece is then attached to surfaces external to itself and possibly of much greater extent than any which are on the piece itself. These being temporary only, may be designed purely for convenience in setting the work during machining and without regard to the subsequent use of the part. For example, the injector body shown in Fig. 111 in section is to be bored in several directions, and various flanges are to be faced.

There are two ways of dealing with it. If one way were adopted the casting could be set with due regard to the thickness of metal and one hole, A, bored. Afterwards by a change of tool, but with the work still clamped as at first, the flange B could be faced. The casting could then be released and reclamped in a position perpendicular to the previous one, by means of the faced flange B. Thus the hole C could be bored, but, owing to its comparative length, any error in setting from the flange B would be multiplied from two to three times in the length of the bore.

The Horizontal Boring Machine and its Possibilities

As an alternative, the casting might have been clamped down on the square table of a boring machine as indicated in Fig. 111 by the dotted outline. Care would have to be taken in setting the piece

on the table in order to ensure that the metal thickness after machining the various bores should be uniform. This would be equally necessary at each setting by the first method. After placing the piece on the square table, each bore would be aligned with the boring spindle in turn; but measurements would be taken on the long sides of the square table which is approximately twice as great as the

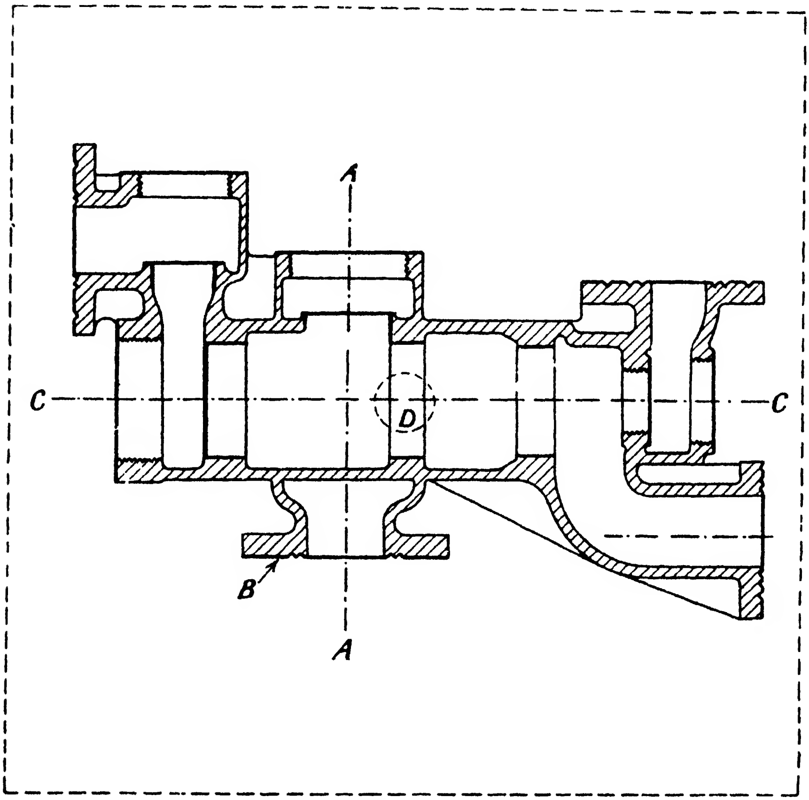


FIG. 111.

longest bore in the work. Any error in setting would therefore be reduced by about half.

The principle involved in the above comparison is clearly one which has many applications where internal surfaces are to be machined in exact relative positions, especially where the machined external faces need be of small extent only.

A very common example of work in which a single clamping is

made to serve for a number of machining operations is the grinding of the several bores in a cylinder block. For this purpose the block is fixed on the table of an internal grinding machine with the cylinder axes all in the same horizontal plane. The axis of one cylinder is then aligned with the axis of the grinding head and the bore is ground. For each of the other bores it is merely necessary to set over the table, carrying the block, by a distance equal to the centre distance of the cylinders. The micrometer feed of the table affords a ready means

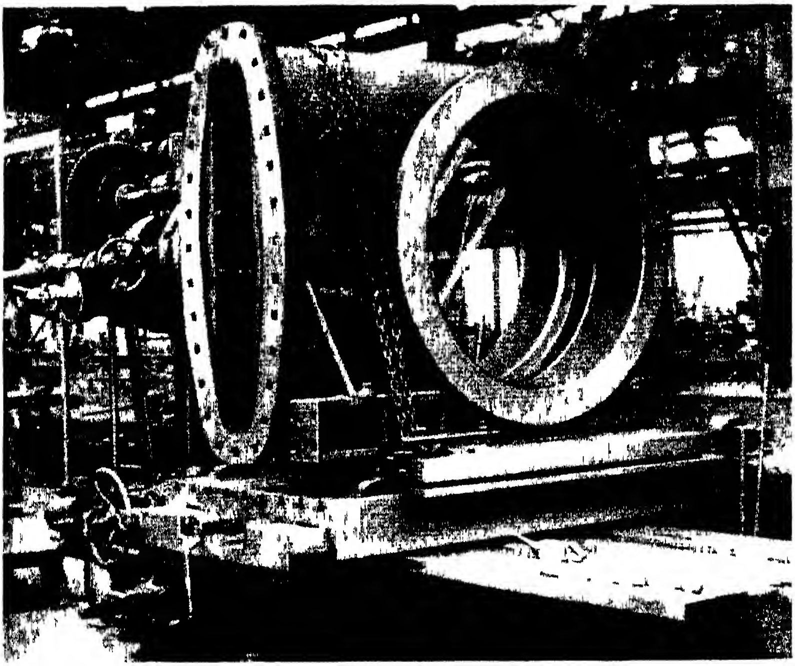


FIG 112

of doing this. Subject to the machine being in reasonably good condition the bores should then be parallel and at the correct centre distance. The precision attained by this method is likely to be much greater than would be obtained by any method which involved reclamping.

Another, and slightly more complex example, is the facing and drilling of a high-pressure valve (Fig. 112). This has faces at right angles, and it will be clamped horizontally on the square table of a boring machine with the flanges parallel to adjacent sides of the

table. One flange is then faced by means of the facing head of the machine. Then any set-screw holes will be drilled and tapped in correct position by the aid of the horizontal cross feed of the table and the vertical feed of the head. The settings for this are very simple if the machine spindle be first set concentric with the flange and then moved to the calculated positions. One flange having been finished thus, the square table is released and rotated through a right angle. This table is machined with its four sides at right angles, and is mounted on a central spigot about which it may be rotated. Stops, which make contact with the sides, enable it to be indexed through 90°. The other flange is thus brought square to the spindle axis and the machining operations are repeated.

The feed motions of the boring machine are in three directions, mutually perpendicular. The square table may be set at any angle to the spindle by means such as are described in Chapter V. By taking full advantage of these adjustments it is possible to machine extremely complicated forms without unclamping the work, and without preliminary marking out.

The following more complex example illustrates the value of the boring machine for intricate machining. The work is a three-cylinder monoblock casting for a locomotive. In the first operation, which is preliminary to setting up on the boring machine, the faces which fit the locomotive frame plates are machined. These faces are then used to locate the casting in a fixture on the boring machine square table. As will be seen from Fig. 113, there are two outside cylinders and three steam chests to be bored with their axes parallel. There is also one inside cylinder with its axis inclined at an angle of one in eight; this is bored as a last operation after tilting the fixture and casting to the specified angle. The five bores first mentioned, together with several plane faces, are machined without releasing the fixture from the square table. A number of plane faces, vertical and horizontal, are faced with milling cutters taking face and side cuts. Some of these faces can be seen in Fig. 113. They are all reached without releasing the casting from the square table, which is indexed to present each side in turn to the milling cutter. Indexing through 90° is accomplished by releasing the clamps and removing a stop, which engages with the tee slot of the machine table and with a notch in each side of the square table. After rotating the work as required, the stop is replaced and the table reclamped, a much simpler operation than resetting the casting alone. The plane faces having been

milled, the five parallel bores are machined with a boring bar which takes the place of the milling cutter.

As each cylinder or steam chest is set for boring, the flange is finished by a tool in the facing head of the machine. The cylinder which is inclined at an angle of one in eight to the others is bored and faced in the same way after the fixture and casting have been tilted. The method of doing this is described on p. 68, in the section on angular settings. It is necessary to make sure that the cylinders already bored remain in the same vertical plane as the work is tilted.

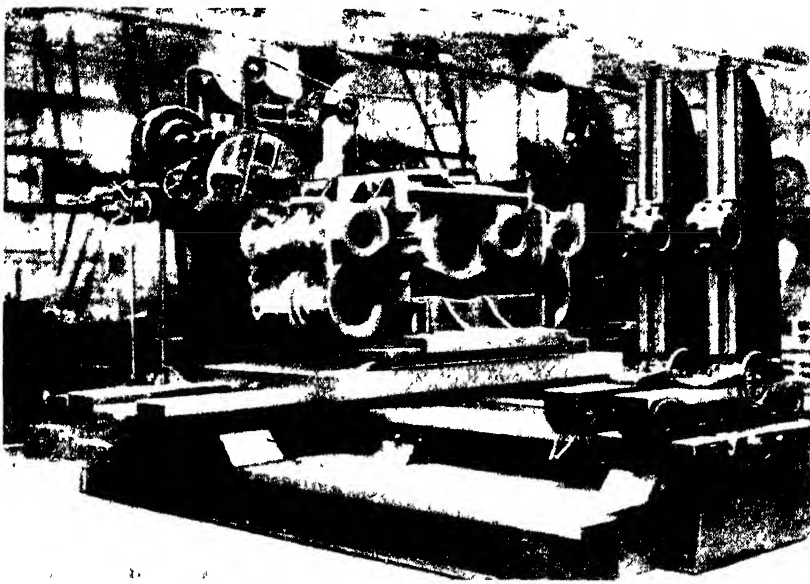


Fig. 113.

This may be done by means of projections on the raising block engaging with the tee slots of the machine table and with one edge of the fixture, if the job occurs often enough to justify a special block. Otherwise measurements may be taken with the aid of a square from one side of the machine table to a convenient face of the fixture.

In passing, it may be remarked that, where tee slots are used for setting as well as for clamping work, the slots should originally be machined parallel to the sides of the table.

Also care should be taken to avoid damaging the slots. A most fruitful source of injury is the use of unsuitable bolts for clamping. Machine bolts should always be a fairly good fit in the slots and should

be faced under the heads so that the pressure may not be concentrated at the extreme edge of the slot.

In reference to the use of traverse and surfacing motions for setting work over through specified distances, setting rods or gauge blocks may be used if there is reason to doubt the accuracy of the machine feed screws. A more detailed description of the method is given on p. 121.

The Master Plate Method

The use of an intermediate piece to which the work is clamped and by means of which it is located as required, is elaborated in the master plate method of boring, which is adopted in die-making and similar work. The master p'ate, besides affording a ready method of duplicating parts with great accuracy, also enables pieces to be set for boring or turning about centres which are either external to the piece or which have been machined away in some earlier operation. The method is frequently used in the production of dies. These must be made within small limits of error, and being subject to wear must be reproduced. The tedious work of setting out and boring the original centre holes is done on the master plate. With careful use the original accuracy of the master plate may be preserved indefinitely. When a number of copies of a given piece are required the piece itself can be used as a master plate. If many copies are required it would be advisable to make a master plate from the piece as a properly made master plate is likely to retain its accuracy better than the actual piece would. Care should be taken to avoid injuring the original when using it as a master plate, *e.g.* by using spacing pieces to prevent drills and boring tools coming into contact with the piece when finishing through holes.

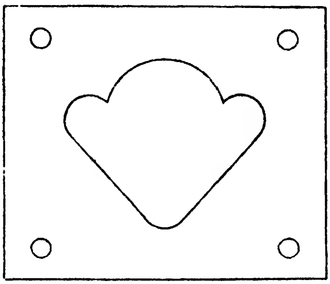


FIG. 114.

A very valuable feature of the master plate method is the possibility of using a set of small centring holes in the master plate to act as centres for setting a piece of work in which very much larger holes are to be bored. The holes in the work may be so large as to break into each other, but in spite of that the arcs so formed will be concentric with the chosen centres. Thus a form which would be

very troublesome by other means may be made and reproduced any number of times with certainty.

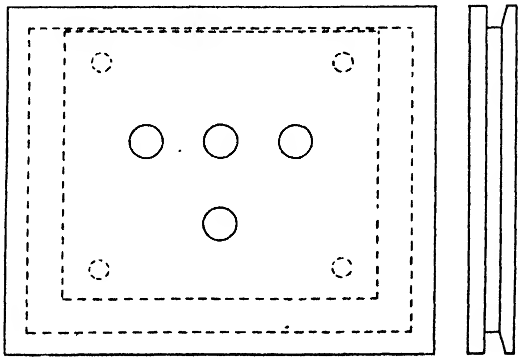


FIG. 115.

The following description of the process of making a simple die with the aid of a master plate will explain the method.

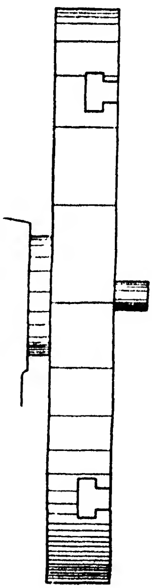


FIG. 116.

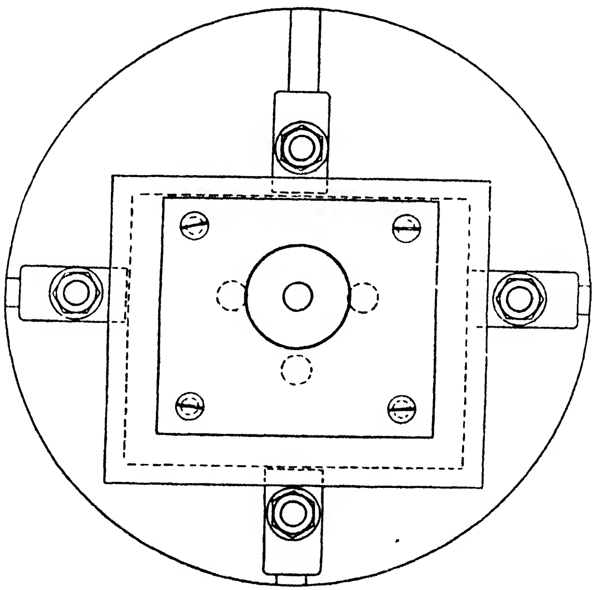


FIG. 117.

The die to be made is shown in Fig. 114. It will be noticed that the outline is partly composed of circular arcs which cut each other. A master plate of steel is prepared, as shown in Fig. 115. This plate

must be large enough to allow a margin round the die and is made with a clamping groove round the edge. It is carefully machined so that its upper and lower faces are parallel. Holes are then set out and bored by one of the methods described in Chapter VII (*e.g.* the button method), at the required centre distances. The holes should be large enough to receive hardened steel bushes if the plate is likely to be used more than a few times. The lathe spindle and

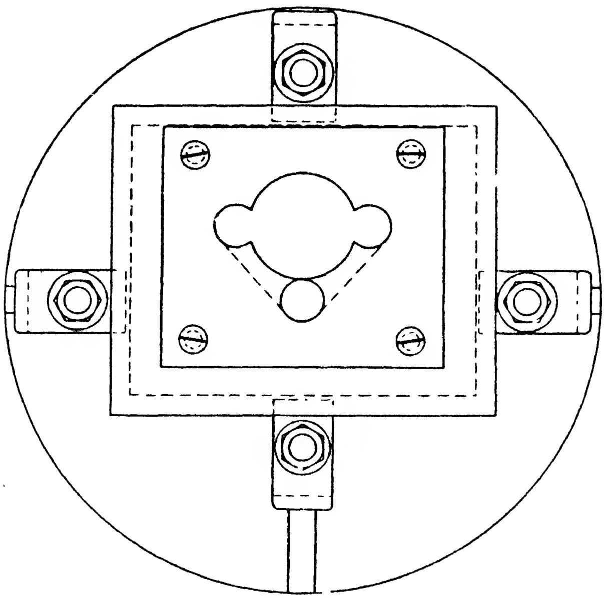


FIG. 118.

face plate on which the boring is done should be in good order. If necessary the face plate must be resurfaced by a light cut.

The die block, having been faced parallel, is attached to the master plate by screws or clamps. It is not afterwards released until all the boring has been done. In order to set the work, a tapered steel plug is fitted in the taper socket of the lathe spindle with a short piece projecting. This projection is turned in place to fit the bushes of the master plate. It is then used to locate the master plate, and the work mounted on it, on each of the centres in turn. The work is then bored to the specified radius in each position. Fig. 116 shows the lathe with the turned spigot projecting, and Fig. 117 shows the work mounted and partly bored. After boring, the work has the

appearance of Fig. 118. The remaining (plane) surfaces are then finished by milling. The precision which may be relied upon by this process (*i.e.* the use of the master plate) is dependent on the use of tool-makers' buttons or equivalent method, and upon the fit of the spigot in the master plate. It should therefore be possible to keep the errors within 0·0002 inch of the specified dimensions.

To show how the master-plate method may be extended to the machining of other forms in addition to simple bored holes a few elementary examples are described. Some of these involve the use of a milling or grinding attachment, carried on the slide rest of the bench lathe. If the work is to be hardened it may be milled near

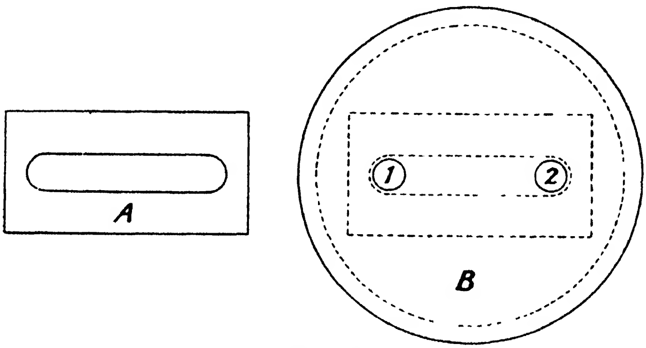


FIG. 119.

to size, hardened and then ground. The same master plate would be used for both the milling and grinding operations.

Take the formation of a parallel slot AB in a steel plate, the ends of the slot being semicircular. The work is shown in Fig. 119 at A, and the master plate at B. The latter is provided with two finished holes spaced to suit the semicircular ends of the slot. A prepared steel block is secured to the master plate. The whole is set on the face plate of the lathe by means of a centring plug in the usual way, and the block is bored in one position. Repeating the process, the second hole is bored. Plugs fitted to the two holes are used to enable them to be set in line parallel to the cross slide. This is done with the aid of an indicator and without releasing the work from the face plate after the second boring operation. A circle of index holes on the edge of the lathe pulley is useful for this setting, especially if the index pin is made vertically adjustable so that its position may be changed slightly.

When the work is set with the two holes horizontally in line, the milling attachment is used with an end mill to cut the slot between the holes. To make sure the slot is symmetrical it is advisable to use a cutter rather smaller than the finished width and to machine each side of the slot alternately by indexing the work through 180°, gradually working to the full depth, leaving a few thousandths for a finishing cut over the whole thickness of the plate.

The depth of this finishing cut is equal to half the specified width of the slot minus half the measured width of the slot as roughed out.

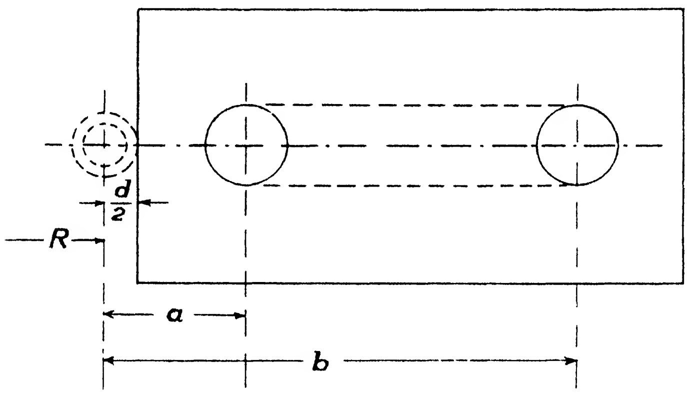


FIG. 120.

To ensure that the slot is milled to the full length without risk of injuring the semicircular ends the distance from each of the two holes to one end of the plate should first be measured, and from these measurements the distance of the centres to the end found. Then the rotating cutter should be very lightly brought into contact with that end and the reading of the horizontal feed dial observed. Adding to this reading the centre distances to the centres of the holes, plus half the diameter of the cutter, the limits for the horizontal traverse will be found. Using these limits, the sides of the slot may be milled to blend neatly with bored holes. If a cutter with a large helix angle (approaching 60°) is available, there need be little or no sign of a groove where the traverse begins or ends. Fig. 120 shows the method and the necessary readings.

A rather more elaborate job is shown in Fig. 121. This is bored as in the previous case, except that the holes are not equal in diameter. To mill the slot each side in turn must be set horizontally by means of the plugs and indicator. After milling one side there may be some difficulty in obtaining a satisfactory fit of the plugs in the work. There may be burrs in the way, or perhaps too much material may have been removed in milling the first side to permit the plug to be securely held, when the master plate may be bored part way through to take two plugs, A and B, of equivalent difference in diameter.

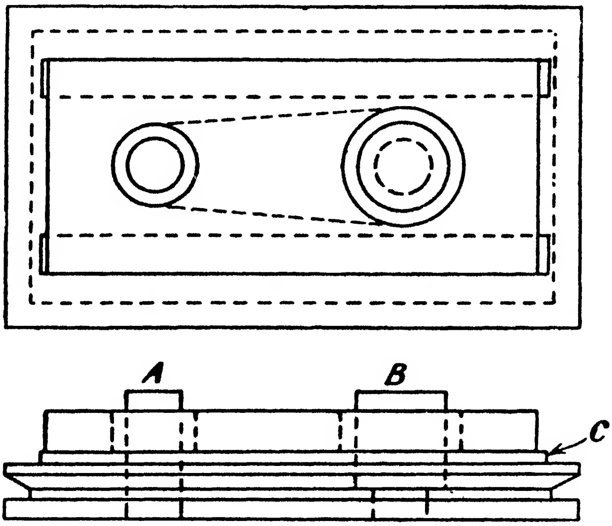


Fig. 121.

These should preferably be less in diameter than the corresponding ends of the slot so that they may easily pass through (see Fig. 121). Packing strips, C, prevent injury to the master plate. A symmetrical slot is ensured by finishing both sides to the same vertical feed reading. The method of limiting the horizontal feed as described in the case of the parallel slot may be used in this case also.

The foregoing descriptions cover the requirements for slots to be finished without hardening. If the pieces are to be hardened the same method will be followed, except that 0·003 inch or 0·004 inch must be left for grinding. After the hardening, the piece will be located on the master plate by means of slightly undersize plugs fitted into holes in the master plate and projecting through the slot. These same plugs may be used also for setting the work horizontally

for grinding the sides of the slot. In other respects the grinding will follow much the same course as was described for finish milling.

For die work the process may be very conveniently modified to give clearance to the die, by setting the top slide of the lathe tool rest

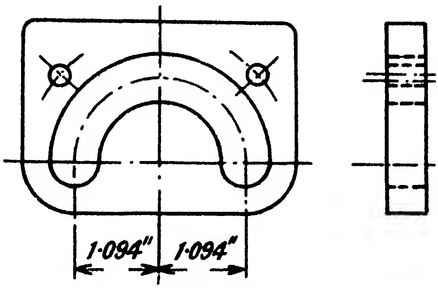


FIG. 122.

at a suitable angle to the bed. Holes are then bored conical instead of parallel. A similar effect may be obtained at the sides of the slot by tilting the axis of the milling or grinding spindle ; but this will require that an independent swivel slide shall be provided unless the slot be machined in the vertical position.

Circular slots may be machined and finished by the aid of a master plate with even greater ease than straight slots. In Fig. 122 a

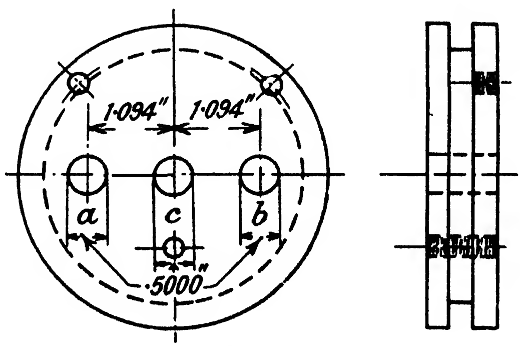


FIG. 123.

circular slot terminating in semicircular ends is drawn. The operations involved in machining this slot are, first, to bore two holes, A and B, for the ends of the slot; second, to mill the slot between the holes with an end mill. For the first operation the holes *a* and *b* in the master plate are used (Fig. 123).

For the second operation, hole C is used to locate the master plate

and work, and the face plate is oscillated through an arc. Some care must be taken to make sure that the sides of the slot merge nicely into the semicircular ends. That is, the arc of oscillation must end at just the right points, otherwise there will be a ridge or a groove near the end of the slot. To limit the arc of movement to the required length, plugs are fitted to the two bored holes *a* and *b*, when the master plate is mounted on the centre, *c*.

Then, with the aid of an indicator, a plug in *a* is set co-axial with the end mill. A stop, D, in Fig. 124, is then clamped to the face plate,

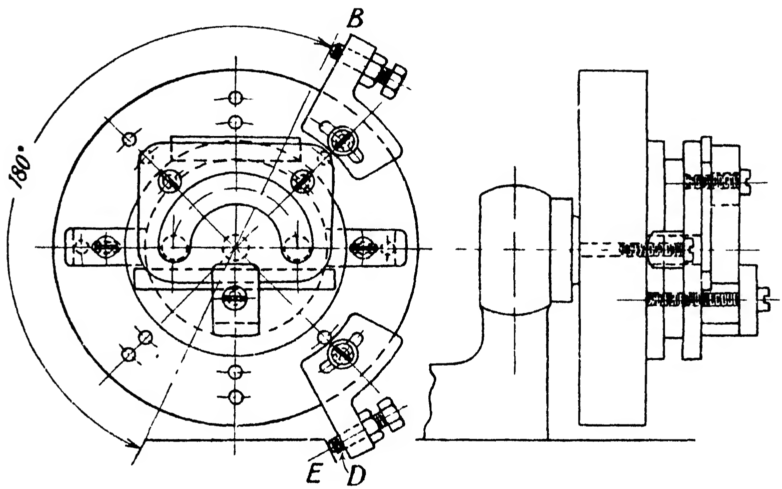


FIG. 124.

so that it is in contact with the lathe bed at E. By repeating these operations for a plug in *b* the rotation of the work is stopped correctly for the other end of the slot. A series of cuts with the end mill, while the face plate is rocked between the two stops, will then cut out the slot as required. There is no need to make the width of the slot equal to the diameter of the end mill. Any wider slot may be cut by using the cross-feed of the slide rest carrying the milling attachment.

Should the work have to be hardened it may be finished by grinding very much as described but with a grinding wheel in place of the cutter.

When a number of holes are to be bored in a circle, an indexing plate may be used as an attachment to the master plate. This will permit a ring of holes to be bored concentrically about a given

centre with rather more facility than is possible with the simple master plate. There is some increased risk of error when additional parts are added in this way, but, given careful work, this objection need not be very serious. The risk attending the use of additional parts must be taken sometimes, as, for instance, when holes are to be bored so closely together as to overlap within the diameter of a minimum size of locating plug. When this happens, the hole in the master plate must be bored large enough to include all the holes.

Several plugs are then made to fit this large hole, and each plug is fitted with a key to prevent rotation. Working from two buttons

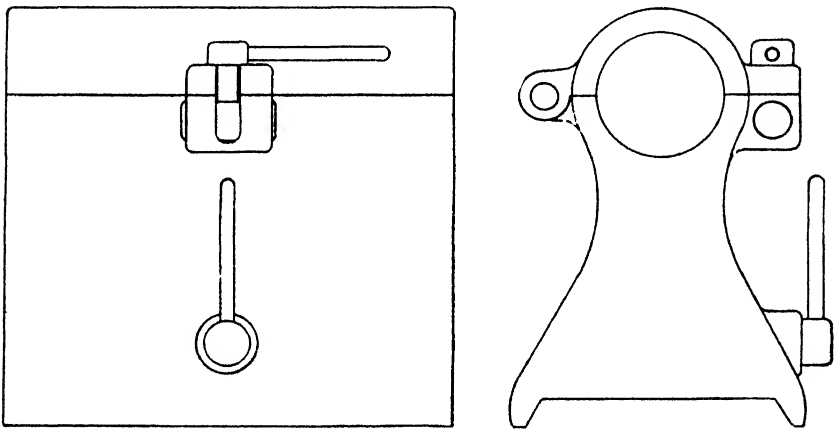


Fig. 125.

suitably placed in the body of the master plate, a button is set in each plug to locate a bore and the plug is bored. In this way a piece involving intersecting holes may be bored by using one master plate and several large plugs interchangeable, and each with an eccentric hole.

It is doubtful if the use of loose plugs, as just described, will give such accurate results as would be obtained by the use of several master plates. A good deal depends upon the fit of the plugs and of the keys. The keys are very important when the plug is bored eccentrically, which is unavoidable for all except one plug. By using a separate master plate for each overlapping hole, the location of the work may be made to depend upon two carefully fitted pins which enter two holes in each master plate in turn. As these pins may be set comparatively far apart, they give more precise location than could be obtained by a key in a plug of small diameter.

The quill rest and quills made by Pratt and Whitney, as an accessory

of their precision bench lathe, may be used in conjunction with the master plate method. This arrangement is used in place of, or rather in addition to, the headstock of the lathe. The quill is a cylindrical sleeve carrying bearings in which is mounted a hardened steel spindle similar to the lathe spindle. Permanently mounted on this spindle is a face plate. The quill rest, shown in Fig. 125, is a block machined to fit the lathe bed and bored out to carry the quill at the centre height of the lathe. Previous to boring, the upper part of the rest is split horizontally and fitted with a hinge and clamp. Thus a quill may be easily removed and replaced in exactly the same position, which is a convenience in work which must be transferred to another machine for an operation and then brought back to the lathe to be finished. The work remains on the quill until finished. Another advantage of the quill is derived from the method of driving, which is by a loose coupling from the lathe spindle. This removes the belt pull with its variations from the work spindle. Smooth running is thus ensured.

The Use of the Lathe for Boring

It occasionally happens that one or more holes are to be bored parallel to faces which have already been machined. This may be done easily if a milling machine be available with a suitable boring tool. But sometimes a lathe must be used, and in such a case the method shown in Fig. 48, which is capable of extension, may be useful. If several holes are to be bored the casting may be reset on parallel strips, lateral settings being obtained by measurement from the side of the angle plate.

Applications of Machines with Several Headstocks Set in Definite Relationship

The unit system of building machines is convenient for machining in quantity. By this system two or more standard headstocks may be set in specified positions relative to each other, which setting may include angular as well as linear relationships. A suitably designed bed with slides is made to carry the heads and the work, which is located either by stops on the frame, or is mounted in a fixture which may be more convenient for handling and setting than the work alone would be. In the latter case the same fixture may be used throughout a series of operations, going with the work from one machine to another. An interesting application of the use of several

headstocks on a common bed is in the milling, drilling and tapping of jute spinning roller stands. This is described in "Machinery," May 3, 1923.

The method of setting headstocks about a specially designed frame as exemplified above is made even more convenient in use by the adoption of electric motor drive for the spindles and hydraulic cylinders for the feed motion. These two devices eliminate a great deal of mechanical complication and render combinations possible which would otherwise be ruled out by the complexity of shafts and gearing which would be required.

Machines with Wide Range of Adjustments of Settings

In some of the components of scientific instruments very intricate forms must be produced. If these are to be made correctly they must be machined by a number of tools without being reset. A very interesting machine, developed by Messrs. Cooke, Troughton and Simms, to deal with this class of work is known as a universal milling and shaping machine for precision work.

In general appearance the machine resembles a lathe, but in place of the usual lathe headstock it carries a special tee-slotted work table with a central spindle and face plate. By this arrangement in conjunction with an ordinary pattern tailstock a wide range of work can be set up. Both top and front of the bed are machined to carry slide rests—that on the top face being regarded as an auxiliary. The principal rest is mounted on the front face and is designed to give a wide range of motions. There is first the horizontal motion of the rest along the bed. On this main slide is carried a vertical slide, terminating in a horizontal circular table. The circular table forms a support for the base of a compound slide rest whose two perpendicular slides may thus be set at any angle in the horizontal plane. This slide rest may be fitted with an extensive range of tools, either rotary, as milling cutters or drills, or simple cutting tools. The latter are operated by lever motions which may be substituted for the ordinary screw feeds of the several slides of the rest. They are hand-operated, but as they are only used for small cuts not easily done by any other means this is no great disadvantage. The variety of slotting and shaping motions, together with the ease of control due to hand-operation, is of great value on small precision work. Almost any direction of cutting in relation to the work is possible, and by means of the shaping motions, interrupted arcs, etc., can be machined.

The Duplex Milling Machine, made by the Van Norman Co. of Springfield, Mass., is provided with such a combination of slides that the cutter spindle may be set at any angle between horizontal and vertical. The cutter head is carried upon a horizontal slide which permits a wide range of adjustment in a direction perpendicular to the table feed. The work-table is supported on slides arranged as in the plain milling machine, which permit of motion along each of three mutually perpendicular axes.

In addition to these adjustments the spindle itself is fitted with an interior sliding spindle which enables a drill or cutter to be fed longitudinally in any direction in which the spindle may be set. With the aid of these various adjustments it is possible to machine many intricate pieces of work without resetting after the work has once been clamped down. In this way not only is the time of resetting saved, but the specified relationship of one machined surface to another may be very much more accurately obtained. Surfaces may be machined either curved or plane in almost any angular relationship without unclamping the work and solely by the adjustments of the machine.

The "Adapta" Milling Machine, made by J. Parkinson & Son, is another example of a machine giving a wide range of motions.

Automatic Die-Sinking Machine with Electrical Control

Another example of the machining of complex surfaces without resetting is found in the making of dies for press work. Some of these dies are of very intricate forms. They are not always built up from simple geometrical elements such as may be easily produced by combinations of straight and circular feed motions. The only method of making the original form may then be a laborious process of working out to measurements by hand. The great objection to this is the likelihood of variations if the original form should have to be replaced on account of wear, or as an alternative the very heavy cost of ensuring similarity. A further objection to the making of actual working dies or tools by hand is the necessity to use a hard steel with the consequent high cost in labour.

These objections to the production of dies and tools by hand are so serious that a great deal of ingenuity has been devoted to the design of die-sinking machines which enable a master form, once made, to be used as model from which any number of copies may be automatically made. The original form is not subjected to the

wear of production work in the press and, although it is used to guide the cutting tool which makes the working dies, it merely acts as an indicator to direct the tool-feeding motions. Since the contact pressures between the master form and the indicator finger are but slight, usually only a few ounces, the master form may be of comparatively soft, easily worked material. Soft metal, wood or plaster are quite satisfactory.

The machine used for this automatic copying process is a specially designed horizontal milling machine, with an electrical controlling mechanism. This may be very briefly described as follows.

Suppose a model or master die to be placed with its working face vertical and above a steel blank to be formed. The tracing finger and an end milling cutter are also placed one above the other with their axes parallel and horizontal. The outline of the milling cutter and of the tracer are similar to each other. The vertical feed motion of this slide carrying the tracer and cutter is set to cover a sufficient distance to include the impression in the master. Stops are set to reverse the motion at top and bottom of the travel, and at each reversal the master and blank are fed a fraction of an inch sideways, *i.e.* horizontally at right angles to the cutter spindle. Under the operation of these two feed motions the tracer and cutter are caused to trace out a series of vertical lines closely spaced and covering the surfaces of the master and blank while they remain at constant distance from the tracer and cutter. This is purely automatic when the stops are set and closely resembles the operation of a tool in planing a surface, although in the die-sinking machine the feed motions are engaged electrically.

In order to follow contours on the surface of the die a feed motion parallel to the cutter spindle is used. This is engaged or disengaged by means of an electrical relay which controls the operation of the feed. The tip of the tracing finger in passing over the surface of the master may reach a hollow so that it is no longer in contact. This permits a very slight motion of the tracer, and an electrical contact is made which acts through the relay and feeds the cutter and tracer in until the tracer again makes contact, when the relay stops the feed. With a very slight increase of pressure the relay is again operated and this time to feed the cutter away from the work. As the vertical feed motion continues a projection may be encountered by the tracer. This will put in motion the outward feed until the contact pressure is again reduced to the equilibrium point.

Thus it appears that the relay controlled horizontal feed always acts to keep the tracing finger lightly in contact with the master form. But the tracer and the cutter are both carried on the same slide and move together. The effect therefore is to make the cutter follow the sectional profile of the master form.

The circuit controlling the relay is of 14 volts, as this low voltage is satisfactory for repeated makes and breaks with very small motions of the contacts. The relay operates switches in the 110-volt circuit which operates the magnetic clutches for the in-and-out feed motions.

The range of motion of the tracer from the full-in to the full-out position is only a few thousandths of an inch, and the point tends to maintain itself in a mean position. Consequently the accuracy of copying is very good. It is claimed that a copy may be made with a variation of only 0·001 inch from the original.

CHAPTER IX

GRADUATION OF SCALES. INDEXING

It sometimes happens that machine shop work involves the graduation of scales which may be straight or circular. These cannot always be sent out to be done on a regular dividing engine, and the possibilities of the machine tools must be considered. The milling machine is the most convenient and, if a universal, may be used for either straight or circular work.

A pointed tool clamped between the washers on the spindle may be used for either kind of work, but unless the work has a true surface will not make a good job. The depth of the marks will not be even, and the appearance will be unsatisfactory. Very much better results will be obtained by the use of a tool which accommodates itself to the surface of the work. A constant pressure will then produce even cuts.

Tools for Graduating

One design of tool for this purpose has a spring-loaded tool. The vee-shaped tool bit is carried in the cylindrical holder so that the cutting point lies in the axis produced. In this position accidental changes in the angular position of the holder have the least effect on the position of the cutting point.

The holder is ground to make a good fit on the tool plunger at each end, and a spring is fitted to apply the pressure needed in cutting. The spring should be fairly long to permit slight variations in the position of the cutter without much change of pressure. An incidental advantage of this length is that the guides will be well separated, and the effect of the necessary clearance for a sliding fit will be very small. Rotation of the cutter may be prevented by cutting a keyway in the holder, but it is better to use a radially projecting pin. The projecting pin slides in a straight slot, which, being at some inches from the axis, is more effective in limiting rotation than a keyway at only a fraction of an inch would be.

An alternative position of the radial pin perpendicular to its original

direction makes the attachment suitable for graduations running parallel to the spindle or at right angles to it.

Another device, even more satisfactory, is shown in Fig. 126. This was made for the graduation of scales lying parallel to the table of the milling machine, and was intended to be bolted to the overarm spindle support. It could easily be modified by the substitution of a differently shaped bracket, to work at right angles to its original direction. It would then be suitable for marking the

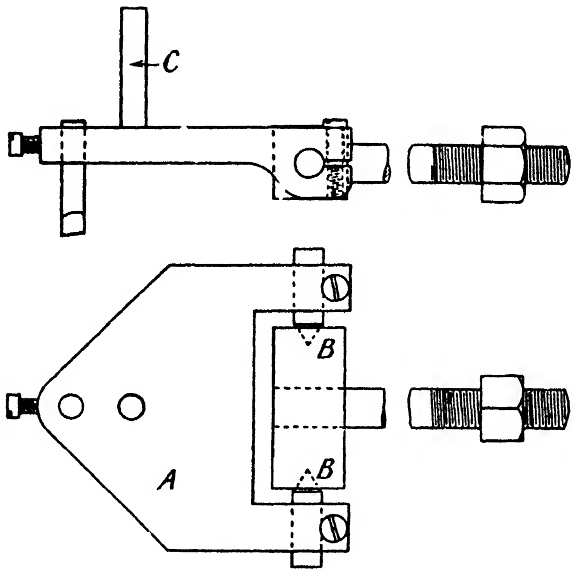


FIG. 126.

edges of discs mounted on centres. The same object might be attained without changing the bracket, merely by turning the cutting point into a position at right angles to that shown, but this would involve a loss of precision if the holder were permitted to swing through more than a few degrees from the horizontal. In most cases this range of swing during the actual marking would not be likely to occur. In any case, since it could only be caused by a very untrue surface the question of precision in the marking would be of minor importance.

The marking point is carried in the holder A which swings on the centre points B. These points are adjustable and may be set up to take out all shake. They should then permit the part A to swing

freely. The depth of marking is adjusted by loose weights placed over the pin C. To avoid difficulty in setting the cutting point, each mark should be started away from the edge of the scale and be made towards the edge. The depth will then depend on the weights C only, provided the point be kept sharp. Except in very deep marking there should be no breaking away at the end of the mark, and there will be no sudden falling of the tool, as it is supported by the clearance face after the edge passes off the scale. Deep marking, or marking in brittle material, may have to be done from the side of the scale inwards. The depth may then be fixed by the use of a distance piece of the same thickness and the same material as the scale. This is placed close by the side of the scale and the marking tool is allowed to rest upon it and to pass from it on to the scale as the mark is made. As a rule, however, it will not be found necessary to adopt this arrangement.

When graduating, the lines are usually of different lengths to indicate the main divisions and the subdivisions. These varying lengths may be obtained by the use of the micrometer feed dial on the cross-feed screw of the machine, but the method is tedious and liable to error.

The application of stops to the cross slide will usually be worth while. These, together with a set of plainly marked distance pieces, one for each length of mark, will simplify the process of graduation and improve the result.

Width of Line for Scale Graduation

Before starting to graduate a scale it is important to form some idea of the accuracy required. For example, if the scale is to be used merely for setting to a mark with the unaided eye, variations not exceeding one-thousandth of an inch will not seriously matter, but if it is to be used with a vernier or viewed with a lens then the error should be kept much smaller than this. How much smaller will depend upon the magnification to be employed in viewing it. As a guide to possible requirements it may be remarked that the verniers in use on height gauges and vernier callipers are readable to one-thousandth of an inch. Errors in the scale should be considerably less than this if the verniers are not to be misleading.

Having decided what accuracy is likely to be required of the scale, the next step is to check the screw which is to be used for dividing, if this is not already known. Although the screws now fitted to

well-made machines are as a rule very true in pitch, it is not advisable to take this for granted even if the machine be new. It is certainly unwise to assume that the pitch of an old or used screw is correct. Milling machine screws are subjected to continual wear, and to fairly heavy loads in proportion to their size, and it is unlikely that the consequent wear will be uniform over the length of the screw. Also there is the chance that at some time the table may have been jammed with the power feed in use, which would be almost sure to have injured the screw.

Test on Screw for Dividing Scales

In order to check the pitch several methods are available. If access to a travelling microscope and standard scale is possible, then it is a good plan to graduate a scale by means of the screw. This scale may then be compared with the standard and variations noted. Some parts may be found quite good and others irregular, and it may be possible to use the better part of the screw, so found, for the graduation of the scale required.

For this purpose it is necessary to note the position of the trial scale with reference to the machine screw. Scales longer than the available length of screw may be graduated if care be taken in resetting the scale longitudinally. Good distance blocks may be used for this purpose.

An alternative method of checking a feed screw is described on p. **306**. This method involves distance blocks and a sensitive indicator. It is at least as reliable as the method described above and is more likely to be within the reach of the ordinary shop. Good distance blocks are now comparatively low in price and have so many applications that few shops, doing general work of good quality, can afford to be without them.

The machine having been tested and found satisfactory so far, the method of dividing remains to be chosen. The most direct method is to use the feed dial of the screw. If the pitch of the screw be one-quarter inch, one two hundred and fiftieth of a revolution gives a traverse of one-thousandth of an inch.

This angular motion is equivalent to a distance of 0·0251 inch at the circumference of a disc 2 inches in diameter. It is rather too small a quantity for accurate setting, and better results will be obtained by the use of a larger disc. The size commonly fitted to milling machine tables is about 2 inches, but if much dividing is to

be done it will be well worth while to substitute a larger disc, of, say, 5 or 6 inches diameter. The 5-inch disc will have one-eighth of an inch spacing under the above conditions. It will be much easier to read than the small disc and will also reduce the effect of small errors in setting.

Application of Spiral Head to Scale Dividing

On a universal milling machine it is possible to make use of the spiral head for longitudinal dividing. By its means the trouble of setting to a line is avoided, because the index plate, B, may be used. This makes available the gearing in the head, which has a forty to

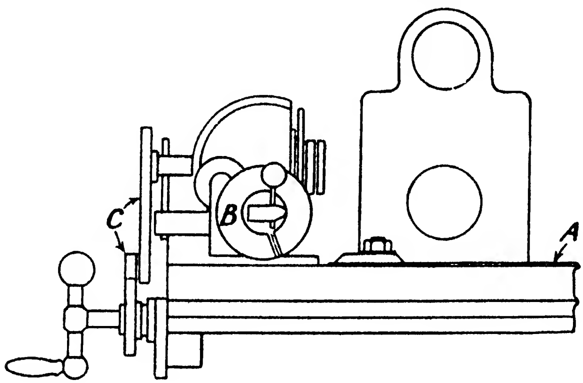


Fig. 127.

one ratio, provided an extended work spindle is fitted to carry the driving gear of the train, C, which connects the head to the feed screw. This arrangement of gearing is shown in Fig. 127, with the work at A.

With equal gears on the work spindle and the feed screw, one revolution of the index crank rotates the screw one-fortieth of a revolution. Thus a traverse of one hundred and sixtieth of an inch is caused. A more convenient arrangement would be obtained by fitting a train of gears of ratio five to four, whereby one revolution of the index crank would cause a traverse of one two-hundredth of an inch. Subdivisions could in either case be made by fractional turns of the crank. For example, one-fifth of a turn in the latter case would give divisions of one-thousandth of an inch. With the aid of a different train of gears and the various fractional turns made possible by the index plates a very great range of graduations is available.

By using the spiral head to operate the feed screw, as described above, several advantages are gained. It is easier to make fractional

revolutions of the screw by means of the index crank and plate than it is to set a scale exactly to a mark without the aid of a lens. The protractor on the index plate may be used as in indexing, so saving the trouble of adding and remembering the reading for each mark. Very often the number of divisions to be added will not be a sub-multiple of 250, so that the readings of the micrometer will not be repeated in every revolution. In such cases there is a tax on the attention which may lead to error and is better avoided by the use of the index plate. Finally, the high ratio gearing of the spiral head acts as a convenient fine adjustment for the screw.

It may be objected that a motion, which depends upon a train of gears, may introduce errors in graduation which would not be likely to occur if the more direct micrometer disc were used.

Let us assume that the worm-wheel has an error of plus or minus

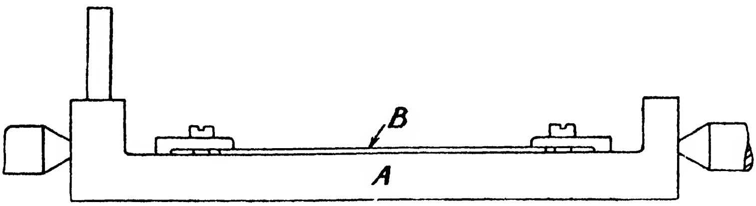


FIG. 128.

three minutes. This should certainly not be exceeded in a machine which is in other respects fit to be used for dividing. Three minutes is 1/7200 revolution, and gives a longitudinal motion of 1/28,800 or 0·000035 inch, through a quarter-inch pitch screw The lead screw would be almost sure to introduce errors several times as great as this. The faults due to the other wheels in the train would be similarly negligible. The universal milling machine is not the only machine which may be used for dividing scales, although its association with wheel cutting may bring it to mind first. Any screw-cutting lathe may be used for the purpose with the addition of a marking tool and some attachment for holding the scale. A suitable attachment is shown in Fig. 128.

The bar A is carried on the lathe centres so that a flat, machined on one side, is parallel to the bed. To this flat side is clamped the scale B, conveniently placed with reference to the marking tool carried in the tool rest. Fractional revolutions of the lead screw to suit a very large range of dividing can be made by means of the change wheels provided for screw cutting.

Train for Metric Division on Inch Pitch Lead Screw

A compound train for metric graduations from a quarter-inch pitch lead screw is shown in Fig. 129. For each half millimetre 20 teeth of the wheel B must be turned past the pointer C. This pointer is an addition to the lathe and may be fitted in any convenient position, as, for example, by a bolt through one of the slots of the banjo plate. Care must be taken to use some definite part of the teeth, say, the leading edge, for setting to the pointer.

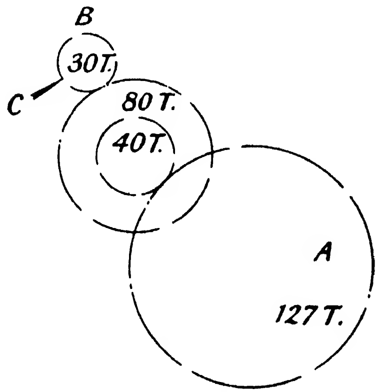


Fig. 129.

With regard to precision, the lathe is likely to be at least as good as the milling machine. In some respects it may even be better. Lead screws are nowadays milled from good master screws and the quality is usually very good. When new there should be little to choose between the lathe and the milling machine, but whereas the milling machine screw is used for all feeding, the lathe screw is reserved for screw cutting, which is usually but a small part of the work done. The lead screw of a lathe is usually of larger diameter than that of a milling machine, since space is more limited in the latter machine. If a long scale is required the comparison is apt to favour the lathe, on account of the longer bed.

In all dividing operations, whether gears are used or not, care must be taken to avoid errors due to backlash, as there is sure to be some play between the screw and the nut.

Circular Dividing

or, as it is more often called, indexing, is familiar in most shops through gear cutting, which is so frequently necessary for repairs and replacements even where it is not a part of the regular shop work. Occasionally a circular scale may be needed, either flat, cylindrical or conical. For all these purposes the spiral head of the universal milling machine is adaptable. One pattern of this appliance is shown in Fig. 130, which is almost self-explanatory. The single threaded worm A meshes with a forty-toothed worm-wheel B. Thus one turn of the index crank and the worm rotates the worm-wheel and the

work spindle through one-fortieth of a revolution. Subdivisions of this fortieth are obtained by a divided plate in which are a number of rings of equally spaced holes varying from 15 to 49 per ring.

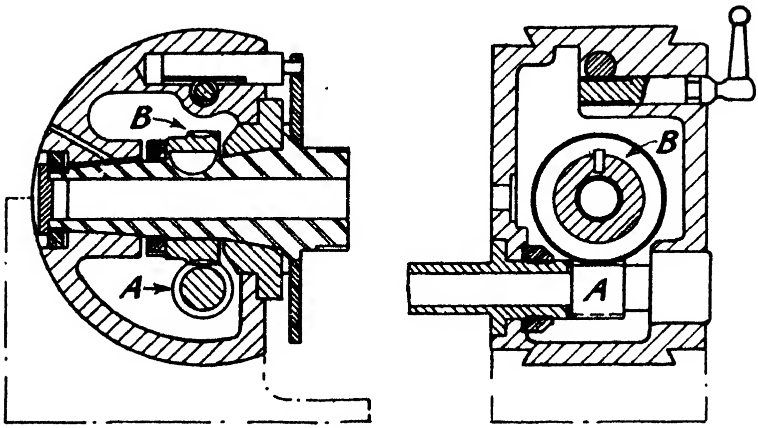


FIG. 130.

The practice of makers of these machines varies in regard to these index plates. Some firms provide large plates carrying many rings of holes, thereby covering all ordinary needs by direct or, as it is commonly known, plain indexing.

Differential Indexing

Other firms prefer to limit the size of their index plates and to use the method known as differential indexing for those cases not directly covered by the plates. This method was introduced by Brown and Sharpe. To use the method the index plate is not fixed to the head, but is mounted on a sleeve which may be rotated by spur gearing (see Fig. 131).

Fractional turns of the index crank, for which no circle of holes is available, are obtained by giving partial rotation to the index plate, so that the motion of the crank plus or minus the motion of the plate is equal to the motion of the index worm required. The motion of the index plate is derived through a train of wheels from the worm gear spindle (that is, from the work spindle). It would seem at first thought that this train must be so complicated that the method would be of little use in practice. Actually it is not so, and most requirements are covered by comparatively few wheels,

most of which would in any case be provided for the formation of spirals and helices.

The example which follows will show how simply the trains work out. A wheel of 127 teeth is to be divided. No suitable index plate is available for plain indexing, but a set of change wheels is provided.

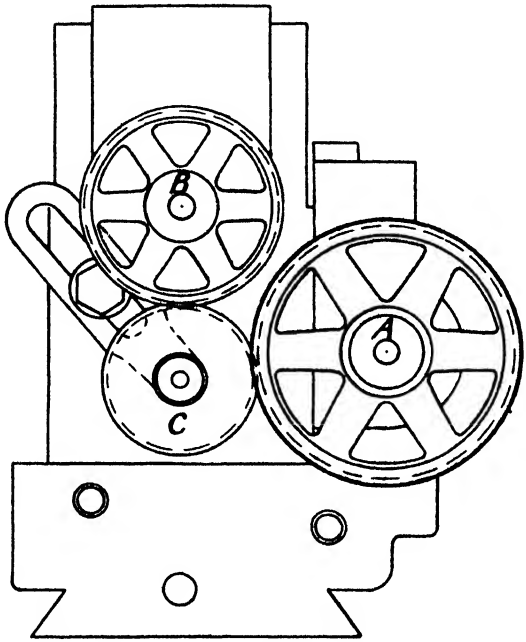


Fig. 131.

By plain indexing, $\frac{1}{120}$ turn of the work may be made,

$$\frac{1}{40} \times \frac{13 \text{ (holes)}}{39 \text{ (circle)}} = \frac{1}{120}$$

This is too great by (1/120–1/127) turn of the work. That is, the index crank must rotate through 40 (1/120–1/127) turn less than 1/3 turn.

A correction must therefore be made, such that, while the index crank moves past thirteen holes on the plate, the plate rotates towards the crank. The necessary motion of the plate is 40 (1/120–1/127) turn. This motion is to be derived from the work spindle by a train of gear wheels, while the work spindle is making 1/127 turn.

$$\frac{\text{Number of revolutions of the work}}{\text{Number of revolutions of the index plate}}$$

$$=\frac{1/127}{40(1/120-1/127)}=1/127\times1/40\times\frac{120\times127}{127\times120}$$

$$=\frac{120}{280}=\frac{3}{7}.$$

This ratio of gearing, which is typical, is not difficult to set up with the change wheels provided as part of the standard outfit of the universal milling machine. It may happen that the ratio found at first trial may not be obtainable from the regular gears. But, in that case, some other fractional turn of the index crank relative to the plate may be chosen. A new ratio of gearing will then follow. As a rule, no more than two trials will be required although many more are possible. In choosing the motion of the crank relative to the plate it is advisable to take values which do not lead to a high ratio of gearing.

The use of a train of gearing in this way is not likely to cause noticeable errors in the indexing, since the gears merely transmit motion from the work spindle to the index plate.

Faults in these gears will therefore bring the index plate into a wrong position and so will affect the position of the index crank. But only one-fortieth of this error will be transmitted to the work through the worm-gearing. With ordinarily well-cut change wheels such an error will be negligible.

The makers of universal milling machines supply tables in which details of the indexing, choice of circles and gear trains are set out. These save the labour of calculation.

From what has been written above it will be realised that ultimately the possible accuracy of an ordinary spiral dividing head depends upon the worm gearing. The division of the index plate is not likely to introduce serious faults. The magnitude of the errors to be expected varies from about plus or minus one minute to very much greater quantities. For example, in one head of good make which had been in ordinary shop use for some years the error was nearly plus or minus two and a half minutes. On the other hand, a good head as it leaves the makers' works should be correct within plus or minus fifty seconds.

Considering these figures in relation to the requirements for the usual run of shop work, the question arises, what precision is needed

for ordinary purposes. Probably the most exacting job of dividing commonly encountered is the grinding of gear-wheels, hardened or soft. For this purpose Mr. H. L. Orcutt, who has done much work in the application and development of gear grinding, stated that one of the greatest difficulties he had to overcome was the lack of precision in dividing. He continued with the statement that to obtain the full advantage of the grinding process he found it necessary to make and use index plates whose error did not exceed $\pm 0{\cdot}0001$ inch at the circumference of a 10-inch diameter circle. This is equivalent to slightly more than plus or minus four seconds, that is, nearly the accuracy claimed for the Zeiss optical head, described below, and very much better than the usual type of spiral head. Such accuracy is not necessary in all cases. In fact, under ordinary conditions of milling very much greater faults are likely to be caused by the other factors, such as, uneven yielding under the pressure of the milling cutter. This is a trouble which is not serious in grinding, since the forces are not great enough to cause appreciable spring in the work or its mounting. Very careful attention is required in milling to ensure that the cutting edges are sharp and run concentrically, otherwise the work cannot be expected to approach a precision of plus or minus four seconds.

The Zeiss Optical Head, Fig. 132, is set by means of a circular scale mounted upon the work spindle and divided into minutes. The distance corresponding to one minute on the circumference of a circle of 7 inches diameter, which is approximately that fitted, is 0·001015 inch. The scale is viewed through a microscope giving a magnification of about sixty diameters. As viewed in this way one minute on the scale is about one-sixteenth of an inch and may easily be halved without serious error. Thus it is possible to set the head to 30 seconds, which is equivalent to an arc of 0·0007 inch on a circle of 10 inches diameter. As the height of centres is $5\frac{1}{8}$ inches, 10 inches is almost the maximum diameter of work which may be carried by the head. The graduated circle is guaranteed to be correct within plus or minus four seconds, consequently the error in any settings, involving whole or half minutes only, should approach this degree of precision. Angles which involve further subdivision of the minute graduations will depend upon the skill used in the estimation of the fractional divisions.

A convenient fine adjustment is fitted, so that there is little difficulty in setting to any angle which may be estimated. Since the

scale is not subject to wear (as the worm-wheel of the usual dividing head is) there should be no loss of precision so long as the spindle and bearings remain in good condition.

No provision is made for driving the spindle by gearing from the table feed screw of a milling machine, and it cannot be used for

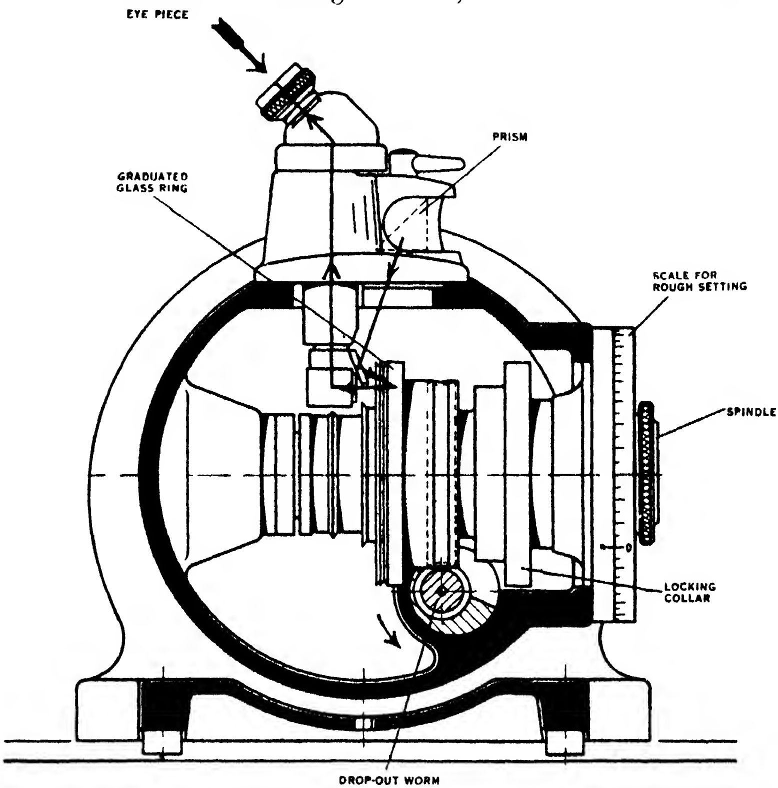


Fig. 132.

cutting spirals or helices, unlike the more usual kind of head. The axis of the spindle is capable of angular adjustment through 90° in a vertical plane.

A dividing head for use with angle gauges and an auto-collimator is described on p. 274.

Sine Bar used to Check Dividing Head

A general machine shop may at any time be required to carry out a job of dividing for which a very small tolerance is specified. Some doubt as to the accuracy of the dividing head available may very

naturally arise. In such a case the following test may easily be applied to verify the head or, if several should be available, to select the most suitable.

First prepare the modified sine bar as shown in Fig. 133. This is bored to fit a plug, C, mounted in the nose of the dividing head spindle and turned truly in place. The disc F, being fixed to the turned plug, provides for the alternate rotation and clamping of the parts E and B of the sine bar by screws D. The other end the bar forms a sliding adjustment for a sensitive indicator, G. By

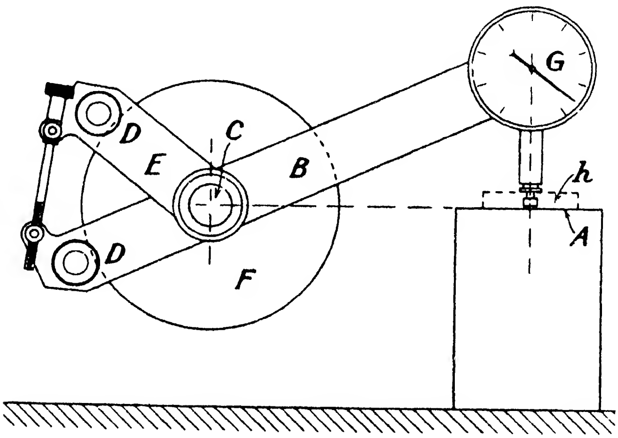


FIG. 133.

this means the contact point of the indicator may be set at some convenient definite distance from the centre of the spindle. Five or 10 inches are most convenient. The indicator should, if possible, be one of those which has a uniform scale reading to ten-thousandths of an inch. This will simplify the work of checking, although it is not essential if a good set of end blocks is at hand.

Having set up the special sine bar on the dividing head, a horizontal flat surface must be placed below the indicator finger. The complete head may be mounted on a couple of parallel strips, to clear the central tongue on the base, on a surface plate, or the head may be left on its own table if the face is in good condition. In any case, a good plane surface must be fixed as at A, Fig. 133, at the height of the centre of the spindle. The axis of the sine bar will be horizontal when the indicator rests on the surface A. A second block of thickness h inches, such that $h/l = \sin\theta$, where l=the length

of the sine bar and θ is some angle at which it is desired to check the accuracy of division, is added to the first.

After placing the second end block over the other the sine bar is clamped to the spindle in the contact position and rotated downwards slightly by the mechanism of the head. This ensures that backlash is taken up all in one direction, and the index pin may be inserted in the plate and a reading of the indicator taken. Next the upper block is removed gently and the sine bar is turned by moving the index crank over the number of holes calculated to rotate the spindle and the sine bar through the chosen angle. This should cause the indicator finger to make contact with the remaining end block, and if the dividing head is correct the indicator will read as before. Any fault in the motion will be indicated by the variation from the previous reading. For the next reading the sine bar must be unclamped from the disc F and rotated backwards until the upper block can be replaced. The indicator is then brought down on the block until it gives a reading about the middle of the scale, using the screw attached to E for fine adjustment, and the bar is reclamped on the pin C. The exact reading of the indicator is then noted, so that after the removal of the upper block and a further partial rotation of the sine bar, any deviation may be observed.

By a repetition of the process any errors in the head may be detected round the full circle. The subdivisions may be as small as desired within the limits of the indexing mechanism, but the smaller they are the more time the test will require.

Division of Large Circles

A problem which sometimes occurs in a general engineering shop is to index a gear-wheel blank of a diameter much greater than any available index plate. The multiplication of error which arises in working from a small diameter to a large one may be outside the permitted tolerance. A process of trial and error setting out on the full diameter may be more nearly correct.

As carried out in the shop it is a refinement of the well-known method of spacing a circle into equal parts by means of dividers. Any error in the spacing is multiplied by the number of spaces and shows very clearly when the complete circuit has been made. To apply the method a pair of stiff arms are pivoted on a central pin in the disc to be divided. Contact screws, as shown on the arm A, engage with a projection on arm B and permit the divider to be moved round in

well-defined steps. One leg is clamped to the work and the other moved on alternately. The micrometer screws enable the length of step to be adjusted very finely as trial shows it to be necessary. In one application of the method the arms are clamped electro-magnetically to the disc, which method is claimed to cause less disturbance of the arm than any other plan. On one of the arms a radially projecting bevelled edge C is formed for the purpose of scribing radial lines on the disc. One such line is drawn and the arms stepped round the specified number of times. The distance between the original line and the final position of the

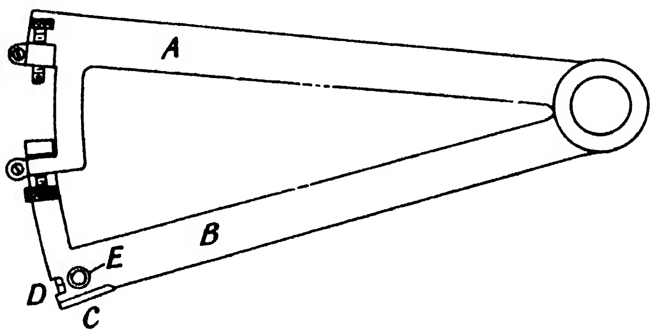


FIG. 134.

bevelled edge shows the accumulated error, which must be divided by the number of steps to give the necessary readjustment of the micrometer stop. The apparatus works with such certainty that astonishingly small time will suffice to find the correct setting. When this is obtained the stepping process is repeated, but a line is carefully scribed on the disc at each new position of the bevelled edge. These lines are used to locate the arm during the next operation, which is the drilling and reaming of index holes in the disc. For this purpose one of the arms is removed and the remaining one, which carries the radial edge, is fitted with a hardened steel bush at some convenient radius as at E. The bevelled edge may be used for location by setting it in coincidence with the scribed lines, but a better plan is to scribe a radial line as at D on the arm leading down to the sharp edge, as in Fig. 134. Any lack of alignment of the two radial scriber marks is much more distinct than the indication to be observed by means of the edge and the line.

Summarising the advantages of the device, it is found that: first,

the correct spacing of the arms is found by means of a magnified or multiplied error; second, the preliminary division of the disc is by marks which require very little force and are therefore unlikely to disturb the setting; third, after marking out, and before any machining is done, the correctness of the marks may be checked by a repetition of the stepping round operation; fourth, any movement likely to lead to an error while the index holes are being drilled is easily observed while it is still rectifiable.

Success depends very largely upon the careful marking of the radial lines on the disc and upon the exact coincidence of the marks when setting the radial arm for drilling the holes. Both of these items will be simplified if the edges of the arm, both radial and tangential, fit snugly to the face of the disc. Unless the radial edge is also to be used for setting to the marks, it need not be bevelled, but the point of the scriber should be more acute than 90°, so that the line will always be drawn directly at the edge. The edge of the arm which carries the indicating line should be brought to a sharp bevel to avoid errors due to changes in the inclination of the line of sight.

Index Plate made with Discs

The following method of preparing an accurately divided circle depends upon the application of very simple machining processes, and with reasonable care will give very good results. Discs of steel shaped as shown in Fig. 92, are very easily made within a small tolerance either by turning or grinding. Grinding is better if a machine is available, and it usually is nowadays. A simple screwed mandrel, which clamps the discs between collars as shown in Fig. 59, is easily made and will often be found useful as the numerous applications of the discs come to be realised. They can be applied to various kinds of dividing, both straight and circular, to setting out angles and to the spacing of holes in jig work.

Considering the application of discs to circular dividing it will be realised that if the discs are equal in size, they need not be finished to any particular diameter. Fig. 135 shows how the discs are employed. A circular plate is turned with a projection, square edged, in the central part as at A. Sufficient discs for the required subdivisions are ground equal in size to each other and of any convenient diameter. When the discs are finished so that they are all of the same size, their diameter is carefully measured. The central

projection of the plate, Fig. 135, is then turned to a diameter which is calculated as below.

Let n=number of equal divisions required.

r=radius of finished discs.

R=radius of central projection.

Then, $(R+r)\sin\dfrac{360}{2n}=r$, since $\dfrac{r}{r_1}=\sin\dfrac{360}{2n}$;

r_1 being equal to $R+r$.

Since r is known by measurement and $\sin\dfrac{360}{2n}$ may be found from the trigonometrical tables, the value of R can easily be found. It will be found more expeditious to work to a calculated value by measure-

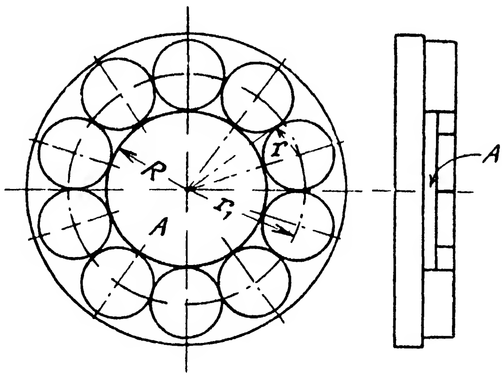


FIG. 135.

ment in this way than it will be to attempt to reduce the central projection by repeated cuts and trials with the discs. It will also be more accurate, because it is difficult to be sure that all the discs make contact with each other and with the central projection, when the size is very nearly approached.

When the discs have been fitted they may be clamped in position by a disc and central screw. To simplify this operation it is advisable to recess the central part of the discs slightly, so that a projecting rim is left. This rim may be easily ground to thickness while the disc is mounted on the mandrel for finishing the diameter. Uniform thickness and squareness with the edge is then ensured and the discs may be clamped firmly in place. When this has been done they will present a notched edge which will serve for the reception of an index pin or plunger. If a more positive form of notch is desired the discs may be made of

half the diameter mentioned, and each alternate disc may be made of double thickness. Thus when the discs are placed around the central projection on the plate, the required number of spaces will be indicated by the alternately projecting discs. The method needs a double number of discs, but has the great advantage of giving a definite contact with a radial face on the indexing pin.

mean value of the diameter of the straight part of the thread outline, except where the radius or the flat at the crest of the thread is greater than that at the root. To cover these exceptional cases it would be better to define the effective diameter as the mean diameter of the working surface of the screw, which definition will include both symmetrical and asymmetrical thread outlines. For the usual form of vee thread the effective diameter is equal to the length of a line passing perpendicularly through the axis and terminating at each end in the straight part of the flank of the thread outline (see *a*, Fig. 136).

The complete examination of a vee thread should begin with the projection of an enlarged shadow of the thread on to a screen by means of a projection lantern, described on p. 277. Comparison of the projected outline with an enlarged diagram will show very plainly any faults there may be in the form of the thread. Such faults are likely to arise from errors in the tool, such as incorrect angle, curvature or irregularity of the flanks, and wrong formation at root or crest. The latter may arise from a slight displacement of the radius tool used to finish the crest when this is done as a second operation. The optical tool-setting device described on p. 89 helps to prevent defects of this kind.

After verification of the outline, measurement of pitch and diameters may be undertaken. These measurements are more troublesome than examination by projection, and should not be made until it is known that no local defect is present to give a false value. Both pitch and diameter measurements depend upon point contacts and may be falsified if there should be a minute depression at the point of contact. A screw might be oversize, but if there were a small groove in the flank at the critical position it might appear to be of the correct effective diameter. Complete general examination of the outline by projection is very easy and would reveal the defect without the trouble of further measurements.

Form, and diameter of thread are controlled very largely by the outline of the tool and the total depth of cut, but the fit of a screw in its nut depends very much upon the pitch, a factor in which errors very easily arise. A vee screw which is long in pitch will not enter a nut of correct pitch unless the effective diameter of the screw is reduced below that of the nut. As may be seen from Fig. 137, it is the total pitch error in the whole length of screw engaged which determines the reduction in effective diameter. Approximately, for

a thread angle 55°, the reduction is equal to twice the total pitch error. It may be found as follows for any thread angle $\theta°$. In Fig. 138 the full lines show a screw which is short in pitch, and the

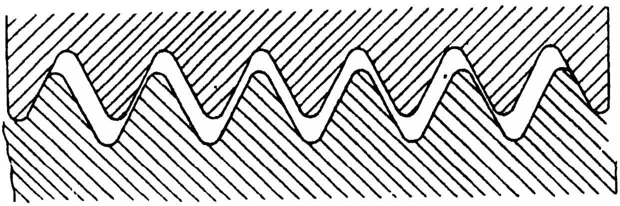


FIG. 137.

dotted lines show a nut of standard pitch. The total pitch error in the length engaged is $2 \times e$, and to permit the two to engage, point a on the nut must drop to b, *i.e.* by a distance $= e \cot \frac{\theta}{2}$. Hence the reduction in diameter must be $2 \times e \times \cot \frac{\theta}{2}$. This is nearly twice the total pitch error for Whitworth threads.

A screw which is out of pitch may usually be detected by the

FIG. 138.

variation in tightness as it is screwed into a correct nut or ring gauge. It may begin to enter easily, but it will gradually tighten as the length of engagement increases. The reason is obvious from Fig. 137.

Pitch

The measurement of the pitch and diameter of screws is described in Chapter XIV, on p. 279. Errors in diameter usually arise from the use of inaccurately formed thread tools, or from the wrong depth in cutting. Errors of pitch in machine-cut (as distinct from die-cut) screws may arise from faults in the machine or may be introduced in a correctly cut screw by subsequent heat treatment. The latter has been a great source of trouble in the manufacture of screw-gauges, which have a very short life unless hardened. If the

alteration in dimensions due to hardening were a constant quantity under given conditions, it would be possible to make allowance for the expected change of pitch when the screw was being cut, but it is almost impossible to ensure the exact reproduction of trial conditions. The small, even imperceptible, variations which creep in are sufficient to prevent the pitch allowance from being quite right. It is almost invariably necessary to correct the pitch of a hardened screw by lapping, which involves a considerable finishing allowance so that the pitch may be corrected before the diameter limits are reached. Thread grinding of hardened screws from the solid has been developed to save the expense of lapping. Both processes are described more fully in Chapter XIII, pp. 247 and 236.

Pitch Errors

Although the actual cutting tool may be a formed tool, a milling cutter or a grinding wheel, the pitch of the resulting screw depends very much on the lead screw of the machine and the train of wheels which connect it with the headstock spindle. If there are faults in the lead screw it is natural that they should appear in the work. A lead screw long in pitch would produce a screw with a similar error distributed in some way over the threads cut, although not necessarily in exactly the same way. For example, a four-thread per inch lead screw having an error of 0·002 inch per foot, used in cutting a four-thread per inch screw, would impart an average error of 0·002 inch per foot to it, even though the error from one thread to another might not be quite the same for both screws. There are two principal sources of error, namely, the mounting of the lead screw and the toothed gearing. It is not uncommon for the thrust collars of the screw to be slightly untrue with the axis. If an untrue thrust collar should make contact with a bearing face which is also not square with the axis, the screw will move bodily endwise once per revolution as shown in Fig. 139, at C. The remedy is to true up the thrust collar very carefully, or to substitute for it a new thrust of the kind mentioned in the N.P.L. report on Screw Gauges. This is illustrated in Fig. 140. The hardened steel bearing ball A is placed in the centre hole at the end of the fixed screw and bears against the hardened steel plate B fitted at one end of the lead screw. The thrust nuts should be slackened to release the screw so that contact is always maintained between B and A. By this arrangement end pressure is limited to an exceedingly small surface near the axis of the screw, so near that

no tilt of the plate B which is likely to occur will cause an appreciable end movement of the screw during its rotation. The thrust plate should be placed so that it will be under pressure when accurate screws are being cut. Usually for right-hand screws the plate should

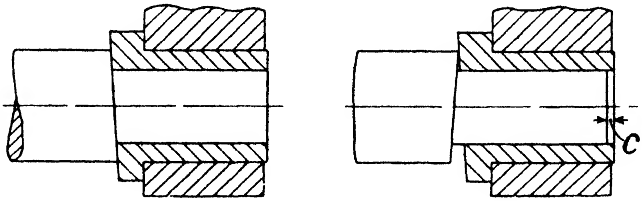


FIG. 139.

be at the right-hand end of the lathe. If both right and left-hand screws are to be cut a plate should be fitted at each end and adjusted so that a very small clearance may exist at the inactive end. The thrust bearings of the main spindle of the machine are likely to be fitted with more care than those of the lead screw, but it is not impossible for an endwise float to occur, with the result that the work will move also and the pitch will be incorrect.

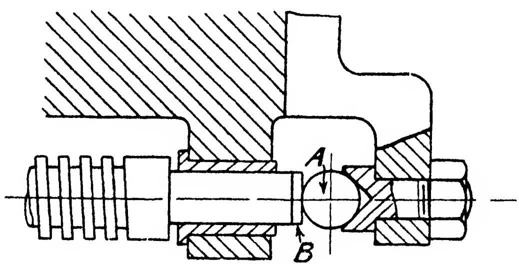


FIG. 140.

Turning next to the effect of faults in the change wheels, errors in the pitch of the teeth of the machine-cut wheels now provided with good machine tools are not often great enough to have any measurable effect on the work. To consider a particular case, suppose that wheel of twenty-four teeth and twelve diametral pitch is placed on a lead screw of four threads per inch. Assuming that one tooth is 0·003 inch out of pitch (an unusually large error for so small a wheel), the motion of the slide rest which this lead screw drives may be calculated as follows. For each revolution of the lead screw the

slide rest should move through one-quarter inch, and if the pitch of the wheel teeth were true, the slide rest should move through one twenty-fourth of one-quarter inch as the wheel rotated through one pitch. But if one tooth is 0·003 inch out of place, when that particular tooth is driven the screw will rotate through one twenty-fourth of a turn plus or minus an error, which is equal to

$$\frac{0{\cdot}003\times7}{22\times2}=\text{revolution.}$$

The effect of this is to move the slide rest through a distance $\frac{0{\cdot}003\times7}{22\times2}\times\frac{1}{4}$ inches more or less than the correct distance. This works out to a little more than one ten-thousandth of an inch error. Even in this extreme case of a small wheel with an abnormally large pitch error the effect on the slide rest is quite small. It would actually be rather less than this because the drive would be shared with adjacent pairs of teeth so that the tooth with the greatest error would tend to leave contact.

A much more serious cause of error is lack of concentricity of the change wheels. In the case just considered, suppose the wheel to be correct in pitch, and assume that it is slightly large in the bore so that it is mounted 0·0005 inch eccentrically, a given motion of the pitch line at the low side of the wheel will cause an angular movement equal to $\frac{0{\cdot}001\times\pi}{2\times\pi}=\frac{1}{2000}$ revolution greater than the same motion would cause if applied at the high side. This corresponds to a variation in the motion of the slide rest equal to $\frac{1}{8000}$ inch, which error would not be reduced by the simultaneous engagement of two or more pairs of teeth. It should be observed that a difference in diameter between the bore of the wheel and the seating on the lead screw of one-thousandth of an inch only is sufficient to cause the above error. Eccentricity of change wheels might easily be due to lack of care in setting them up in the gear-cutting machine. Slackness in the bore might then either nullify or intensify the fault according to the manner of placing the wheel. In any case, it is clearly a more serious source of error than the usual variations in the pitch of teeth.

When a trial screw has been cut and the pitch of the thread proves to be faulty it becomes necessary to locate the cause. This is con-

veniently done by plotting the variations, plus or minus, from true pitch as sketched in Fig. 141. The variations are plotted as ordinates against the true pitch as abscissæ. If a sufficient length of screw is

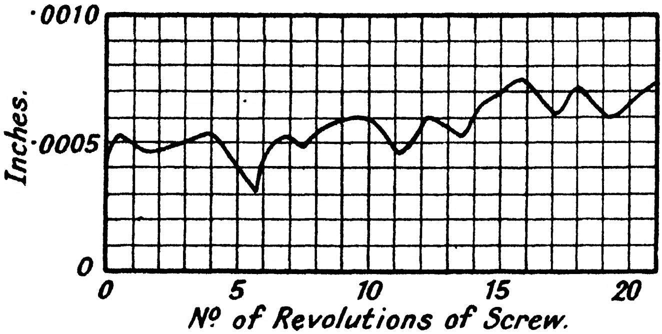


FIG. 141.

measured, a periodicity will be perceived. Possibly more than one may be traced. In the case shown the thread cut is nominally 14 threads per inch, and the lead screw is 4 threads per inch. The train of change wheels is shown in Fig. 142. Wheel 70 T rotates 4 times per 14 threads of the tested screw ; wheels 60 and 30 28 times per 42 threads ; wheel 40 T rotates once per thread. Examination of the diagram shows a recurring cycle every three and a half threads, partly disguised by other periods. This may be due to endwise motion of the lead screw or to eccentricity of the wheel 70 T. A sensitive indicator or dial gauge graduated in ten-thousandths of an inch would reveal any endlong motion of the lead screw.

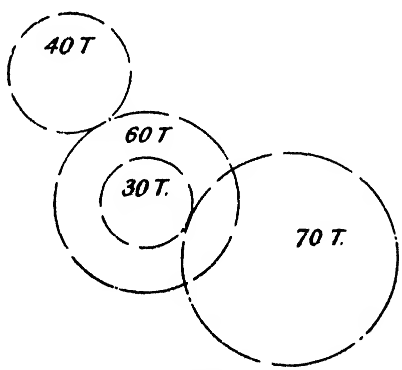


FIG. 142.

To eliminate the effect of a faulty end surface on the lead screw a ball should be placed in the centre of the screw and used against a flat surface on the indicator G (see Fig. 143). If no motion is detected here the wheel 70 T should be examined. The other periodic errors are traced out similarly and eliminated one by one. For very accurate screw cutting, as required for micrometers, the successive elimination

of errors in the thread grinding machines may be a long and tedious process, sometimes involving the dismantling and refitting of the machine many times.

The errors in pitch discussed above are of the periodic kind. There is also the progressive error which increases with the length of screw and shown by the gradual slope of the curve. This may be caused by a faulty lead screw or possibly by variation of temperature of the work while the thread is being cut. If a screw 10 inches long were to rise an average of 10° F. above room temperature while being cut it would be $10 \times 10 \times 0{\cdot}000006 = 0{\cdot}0006$ inch short in the whole length after cooling. It is clear that great care must be taken to

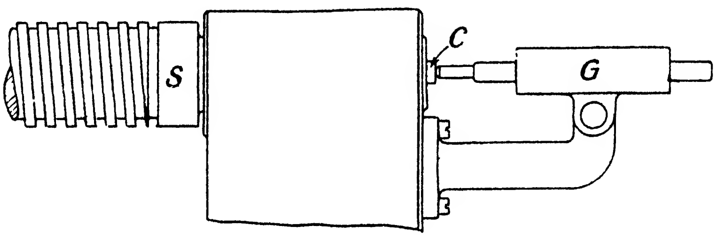


FIG. 143.

avoid change of temperature in cutting precision screws. Moderate cutting speeds and ample supplies of cooling liquid are essential.

In connection with the periodic errors of a screw, it is to be remembered that the measured errors from thread to thread are usually greater than the errors which will arise from the actual use of the screw in question. The screw is not applied by contact with a single thread, but is usually fitted with a nut covering several threads. Periodic errors recurring in a part of the screw less than the length of the nut would be smoothed out by the distributed contact. Serious periodic errors would, however, be likely to cause rapid wear because of the localised contact.

Pitch Correction

When an accurate screw is to be made, and the only lathe available has a lead screw of less than the needed accuracy of pitch, it is possible to fit a device to make allowance for the pitch error. It is taken for granted that other sources of error have been examined and eliminated. The motion of the slide rest under the action of the lead screw is measured and the errors are plotted against the desired true motion

of the slide rest as a base. The necessary measurements are made as described on p. 306, with the clasp nut in mesh with the lead screw. The curve of errors obtained in this way is formed on the edge of a steel template A, Fig. 144. It is then used to give a partial rotation to the screw B in Fig. 144. This screw B compensates for the pitch errors of the lead screw by causing it to move longitudinally through a small distance. Thus the motion of the slide rest is derived partly from the rotation of the lead screw in its clasp nut and partly from the slight longitudinal movement of the lead screw. When this apparatus is used the thrust collars on the lead screw must be slacked off sufficiently to give longitudinal freedom.

The scale to which the pitch errors must be plotted for the template will depend upon the dimensions of the mechanism, namely,

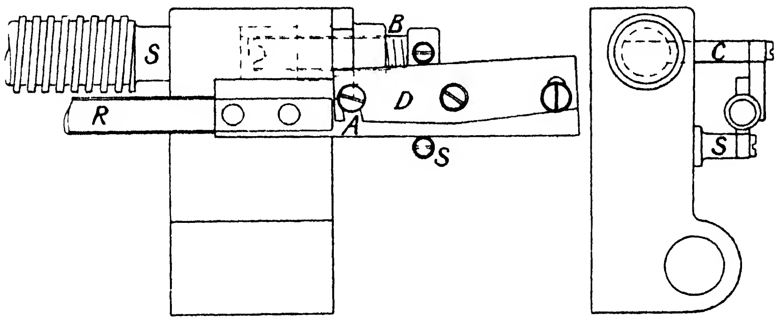


Fig. 144.

the pitch of the screw B, and the radial length of the arm C. Suppose, for example, that the pitch of B is one-tenth of an inch and that the effective length of arm C is 9 inches. Then, in order to transmit a motion of one-thousandth of an inch to the lead screw, the end of the arm would have to move through an arc of length equal to one-hundredth of the circumference of a circle of radius 9 inches. This is equal to 0·283 inch. Other errors would require proportionately greater or less motion of the arm. The screw B must be placed at the compression end of the lead screw, which will depend upon whether right or left-hand screws are to be cut. Either a weight or a spring will serve to hold the arm in contact with the correcting template.

A somewhat similar mechanism is used on Alfred Herbert's precision screw-cutting lathe. This lathe is specially made for the production of accurate screw gauges. It is fitted with an inclinable

slot which controls the position of a lever attached to the nut on the slide rest. If this slot is set horizontally the lever is not moved either up or down, and the nut is not rotated. But if the slot is set at an angle the lever moves as the slide rest traverses past the slot,

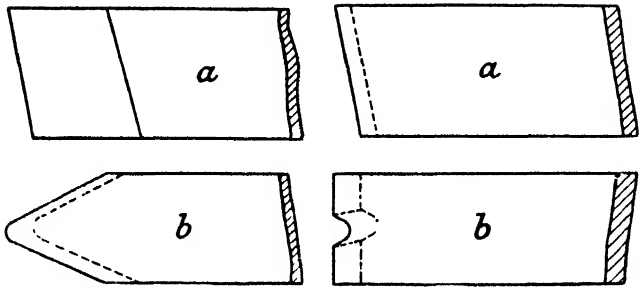


FIG. 145a. FIG. 145b.

and the nut is partially rotated. Thus the motion of the rest is either a little more or a little less than it would be if the nut were not rotated. This is easy to understand if one imagines the lead screw to be stationary and the nut to be rotated by the given amount.

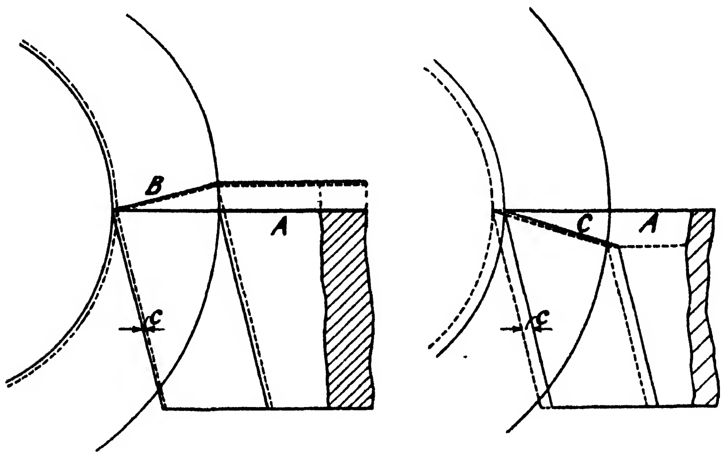


FIG. 146a. FIG. 146b.

The motion so given to the slide rest will be added to or subtracted from the motion derived from the rotation of the lead screw.

Tools used for screw cutting in the lathe are formed to the thread profile. In Fig. 145a a tool for cutting the groove of a thread is

shown in elevation and plan at *a* and *b* respectively. For finishing the crest the tool shown in Fig. 145b is used.

The depth of the thread may be varied with a given formed tool by grinding the top rake differently. As will be seen in Fig. 146, negative rake will produce a shallower thread and positive rake a deeper thread. If these variations are kept within narrow limits there will be no appreciable change in the general outline, for example, the flanks will remain straight and the curvature of the crest and root will not be measurably altered. The control of depth in this way by grinding is very convenient when cutting screws, as for instance gauges, which must fall within extremely narrow limits in the relations between crest, effective and root diameters. The following example

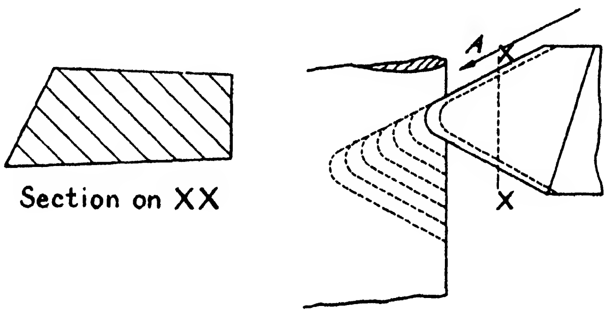


FIG. 147.

will indicate the possibilities of the method. A 1-inch standard Whitworth screw has a depth of 0·080 inch. A tool which is formed to the correct outline with zero top rake will cut a thread which will be 0·0001 inch deep or shallow if it be ground with plus or minus $2\frac{1}{2}°$ of rake respectively.

Time may be saved when cutting screws by the use of a tool ground to have considerable side rake. This tool is used as shown diagrammatically in Fig. 147. The tool is fed in parallel to one flank of the thread and cuts entirely on the other flank. With this tool comparatively heavy cuts can be taken, which is not possible with a tool cutting on both flanks. Chips converging on the top of a tool cutting on both flanks concentrate pressure near the point of the tool so that any but very light cuts will cause fracture. The tool with side rake cuts freely, but must be followed by the usual flat top tool to finish the screw correctly to form.

Methods of Cutting Screws

As mentioned, the possibility of the errors discussed above is common to all the processes which depend on traversing a cutting tool along a revolving cylinder. In practice, the milling process seems to be supplanting the use of a single-edged cutting tool for the manufacture of precision screws for feed motions. Very good screws are produced by milling. The advantages in comparison with the older process being, first, the reduced wear on the master screw owing to the fewer traverses involved per screw, and, second, the decreased liability of the milling cutter to be deflected by variations in the material of the screw blank. The latter advantage is even more noticeable in the ground thread because the forces are very much less than in milling. But the principal value of grinding lies in the ability to correct hardened threads or to cut them from the plain hardened blank.

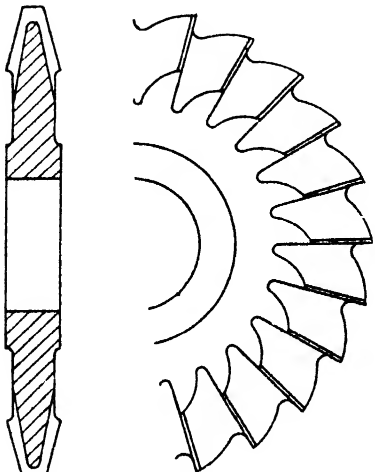


Fig. 148.

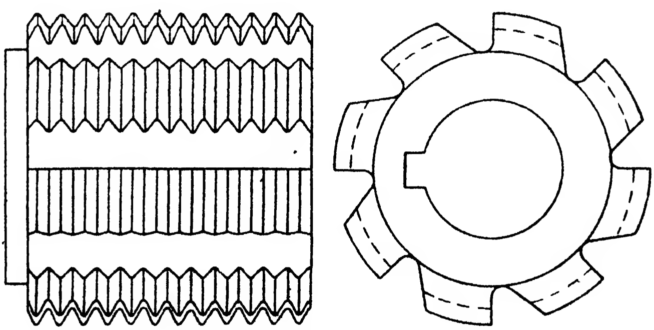


Fig. 149.

There are certain limitations on the form of thread which may be cut by milling, and these operate even more severely in the hobbing process. The distinction between milling and hobbing lies principally in the kind of cutter used. Fig. 148 shows the single cutter used in

milling the acme thread; Fig. 149 shows a multi-grooved cutter for milling vee threads, and Fig. 150 shows a hob for vee threads. The teeth in cutter of Fig. 149 are placed in rings perpendicular to the cutter axis. In this cutter there are in effect several single cutters side by side, although they are all formed in one piece of steel. The essential and common feature of both cutters, Figs. 148 and 149, is that on rotation about the axis each tooth in a ring will pass through the same position in turn. When such cutters are used to form a screw thread they must be moved endwise by one pitch for each revolution of the screw to be formed. This axial motion may be entirely independent of the number of revolutions of the cutter. In other words, such a cutter is used as a substitute for an ordinary screw-cutting tool and, apart from its rotation, in the same way. A hob, on the other hand, has teeth placed along a helical line, con-

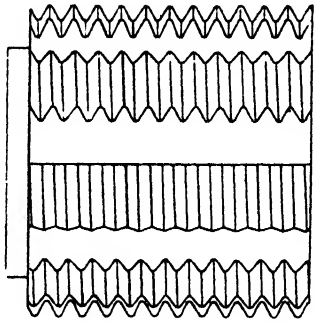


Fig. 150.

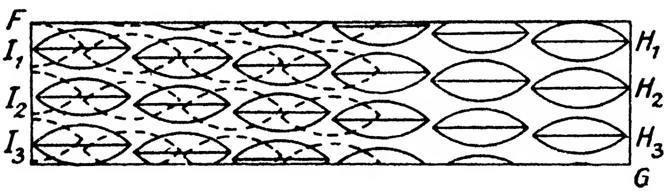


Fig. 151.

sequently as it rotates about its axis each tooth will pass through an axial plane, in a position a little to the right or left of the previous tooth. Obviously if a hob were rotated in contact with a fixed piece of metal it would cut a series of notches, each one slightly displaced with reference to the previous one. These notches would overlap, and finally, almost the whole of the edge of the piece would be removed to the depth of the thread. But if the piece of metal were moved steadily across the axis of the hob, from H to I, in Fig. 151, during one rotation of the hob, the appearance of the cuts made by the hob would be as shown in Fig. 151. If the

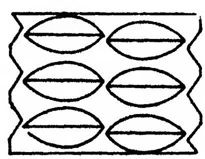


Fig. 152.

surface of FG were rolled into a cylinder the points H_1, H_2, etc., would join up with the points I_1, I_2, etc., the result would be a rudimentary screw thread (Fig. 152). During a second rotation of the hob in contact with the cylinder formed as described, each tooth of the hob would fall into the notches already formed, and no more metal would be removed during the second or any later revolution. A screw thread formed in this way would actually consist of a limited number of facets which would depend on the number of teeth in each turn of the hob thread. This is a disadvantage if well-formed threads are required. It has been reduced by a creep gear in the Richards thread hobbing machine. The hob in this machine is driven by a worm-wheel mounted on the hob shaft. In order to bring the cutter teeth to slightly different places in successive revolutions of the work, the worm which drives the hob is given a very slight cyclical endlong motion, such that the worm moves slightly to the left for nine and a half revolutions and returns during the next nine and a half revolutions. The effect of this is to increase the speed of the hob during one part of the cycle and to reduce it for the remainder. The change of speed is very slight, but it is sufficient to prevent the teeth falling exactly into the same tooth marks each time they come round. The period of the cyclical motion of the driving worm is not exactly equal to the time of one revolution of the hob. Consequently the work and the hob do not reassume their initial positions until after several revolutions of the work. The effect is shown in the dotted lines in Fig. 151. In that time the number of facets formed on the thread becomes so great that for all practical purposes the thread may be taken as smooth.

In addition to increasing the number of facets the creep gear has another effect, namely, that the pitch of the thread being cut tends to be increased for a period and then reduced for a period. The actual variation in pitch is very small, but if it were magnified to become visible, the thread would appear to undulate about its mean position. But in successive revolutions of the work the undulations are smoothed off and the final effect is to produce a smooth thread of slightly less thickness than the groove in the hob. This thinning of the thread can be allowed for by making the hob thread thinner than standard.

In milling, since the speed of the cutter is not related to the speed of the work, there is no difficulty in making the size of the facets as small as may be desired.

Interference in Screw Milling and Hobbing

It is obvious that if either a hob or a multi-threaded cutter is to be engaged for its full length it must be set with its axis parallel to that of the thread to be cut. The simple milling cutter may be set at a slope so that it lies approximately in the direction of the thread, although in practice it is very often set parallel, like a hob. It is the possibility of setting the cutter in the general direction of the thread that gives rather greater range of form to the milling process with single cutter as compared with hobbing or multi-cutter milling. Both methods are liable to interference between the sides of the thread and the teeth of the cutter as they enter and leave the work with the result that the outline of the groove may not be a copy of the outline of the cutter teeth. As an example, to show the effect of interference, consider an ordinary side and face cutter as shown in Fig. 153. If this be rotated while a piece of work is traversed below

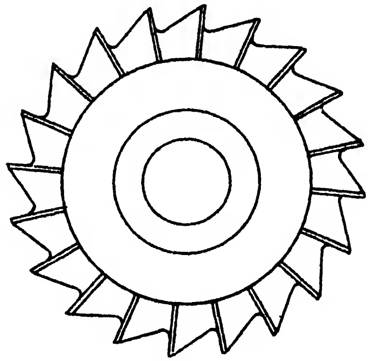


Fig. 153.

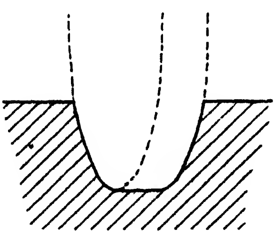


Fig. 154.

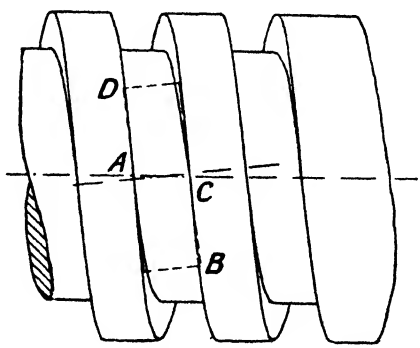


Fig. 155.

it in a direction parallel to the plane of the cutter it will cut a groove of a cross-section like the outline of the cutter teeth. But if the work be traversed in the direction parallel to the cutter axis the groove will not at all resemble the shape of the cutting edges. It will be a segment of a circle. Directions of feed intermediate between these

will produce grooves as shown in Fig. 154, composed of two elliptical arcs and a straight line. If the projection of a square thread screw be examined it will be obvious that a plane surface tangent at A, Fig. 155, will foul the screw at D. Also that a parallel plane tangent to the other thread at C will foul at B. The two parallel planes represent the two sides of a side and face cutter. Such a cutter, of width equal to the full width of the thread groove, could not in any way be inserted between the threads without cutting into them,

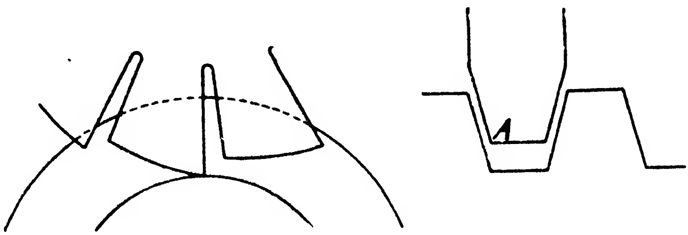


FIG. 156.

although least damage would be done if the plane of the cutter were tangential to the helix at A. A square thread can only be milled with an end milling cutter, but a thread with sloping sides, such as the acme thread, can be milled with a cutter of the form shown in Fig. 156. The thread made by this cutter is narrowest at the root so that the point A on the cutter, as it sweeps round in a circular path out of engagement, passes into a wider part of the groove and tends to clear. This tendency is to some extent counteracted by the curvature of the helix, which causes the flank of the thread to approach the cutter. The case of interference which occurs when the axis of the cutter is parallel to the axis of the screw covers many of the thread milling or hobbing machines in common use. The calculation of the cutter form for this case is not difficult.

Correction for Interference

Allowance for interference is made by altering the angle of the cutter teeth. The corrected outline is found as follows.

Referring to Fig. 157, it is clear that the extreme point d of the cutter, as it leaves the common central plane of the cutter and screw, departs from the finished outline by an amount x; but owing to the curvature of the helix one flank of the thread approaches the plane of the cutter. The algebraic sum of these two effects is the amount

of the interference to be expected in any particular case. In Fig. 157, d is the extreme corner of the cutter after rotation through an angle β from the line of centres. The axial displacement of a point in the flank of the thread between positions B and A is equal to $\frac{a \times p}{360}$ where p=pitch of thread. If the effect of the helix were neglected

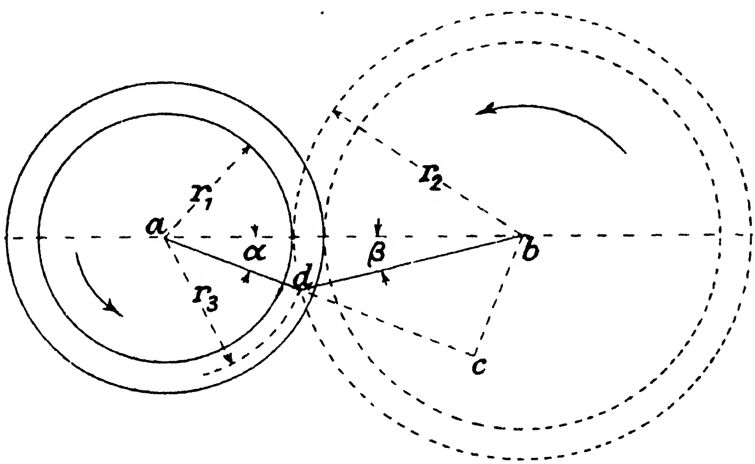


Fig. 157.

there would be a clearance owing to the slope of the flanks equal to $x \times \tan \gamma/2$, where γ is the thread angle, and $x = r_3 - r_1$.

Therefore the effective clearance is equal to

$$x \times \tan \frac{\gamma}{2} - \frac{a}{360} \times p.$$

If this expression should be negative there will be interference. The distance x is found as follows for any particular value of the angle β:

$$ab \sin a = bc.$$

$$\frac{bc}{r_2} = \sin (a+\beta)$$

$$\therefore \frac{ab}{r_2} . \sin a = \sin (a+\beta),$$

or

$$\left(\frac{r_1+r_2}{r_2}\right) \sin a = \sin (a+\beta)$$

$$r_3 \sin a = r_2 \sin \beta$$

$$r_3 = r_2 \sin \beta \div \sin a$$

and

$$x = r_3 - r_1.$$

From these relationships the clearance or interference for various values of α and β may be found. If there should prove to be interference, it is usually possible to make a correction of the cutter shape which will produce the thread required provided that some clearance may be allowed at the root of thread. The latter is necessary because there is no method by which a rounded fillet between the root and flank of the thread may be eliminated in a single milling operation of the kind discussed above. The fillet is in practice very small, and will as a rule fall within the normal clearance allowed between the crest and root of acme threads. If it should not do so, there is no great objection to a small increase of the root clearance. It will very slightly reduce the strength of the screw, but there is sufficient margin to permit this with safety. The wearing surface is not reduced, and this is the limiting factor in selecting the dimensions for acme screws.

To determine the shape of tooth required, if interference should be found to occur with the standard form, several values of β should be taken and calculations made to find the position of maximum interference. Also the calculations should be repeated for two or three points, at various radii on the side of the cutter. Combining all the results, it will be found that a cutter tooth of a slightly increased angle and with very nearly straight sides will produce the required thread. The sides may generally be made straight as the curvature of the corrected form is almost imperceptible. For ordinary vee threads of Whitworth or similar form interference is not likely to occur unless the pitch is unusually large in proportion to the diameter. In the calculations discussed above, it has been assumed that the cutter axis is set parallel to the axis of the screw, but if screws of steep pitch are to be cut the cutter must be set over to the mean helix angle of the screw. There may still be some interference, but only if the thread is approximating to the square form.

The calculation of the corrected form of cutter is much more troublesome when the axis is not parallel to the axis of the screw. Although mathematical expressions for the corrected form are obtainable,* they are rather tedious to use, and, for those unfamiliar with them, difficult to interpret. But, once the necessary calculations have been made, the results may easily be applied to the formation of a cutter by means of the projection lantern. This is described

* "The Milling of Screws and other Problems in the Theory of Screw Threads," H. H. Jeffcott, D.Sc., Proc. I. Mech. E., 1922, Vol. I.

on p. **277**. The calculated results are used to plot an enlarged diagram of the required form, from twenty to fifty times actual size as may be convenient. By comparison of the projection of the tool with this diagram the tool may be formed with great accuracy.

In practice, however, when the calculations necessary for plotting the diagram are somewhat intricate as in this case, most mechanics will prefer to use other methods for producing the corrected cutter or hob.

One such method is to work backwards from the required screw thread to the cutter. For example, in the case of the Richards thread-hobbing machine there is not only the effect of the different thread inclination to allow for, but in addition the effect of the to-and-fro float of the creep mechanism. For this machine the first step in the preparation of the hob is to make a screw similar to the desired product. This screw is then gashed, relieved and hardened so that it becomes a hob itself. It is then set up to act upon a cutter blank so that the relative motion of the work and the final hob will be reproduced. The cutter so formed will in most cases have the outline necessary for the hob teeth, and may be used in the production of the final hob. Some details of the later steps in the process are given in Chapter XI, p. **203**.

One interesting method of screw-thread production involves the use of a cutter similar in form to those used in the Fellowes gear generating machines. These cutters for gears are formed with teeth whose section by a plane perpendicular to the axis of the cutter is that of an involute gear tooth. Such a tooth meshes with a rack of appropriate angle. If it be made as a cutter and so arranged that it cuts while its pitch line rolls along the pitch line of a suitable blank, it will form straight-sided rack teeth in the blank. In the Fellowes gear shaping machine the necessary cutting motion is obtained by reciprocating the cutter axially as it is caused to roll round the blank. For the purpose of forming a screw thread the reciprocating motion is not required, because the necessary cutting movement is provided by the rotation of the screw blank. As the screw is rotated and observed against a light background the threads in silhouette will appear to move sideways, like a rack moving endways. In each revolution the threads will appear to move one pitch. This is helpful to remember when thinking of the gearing which must be applied to the rotary tooth type cutter for screw cutting. Imagine a screw to make one revolution on its axis and a cutter to be mounted

on a fixed axis perpendicular to the screw. For each revolution of the screw the cutter must rotate through the space of one tooth. If, instead of remaining in one place, the axis of the cutter be traversed along the screw at the speed of an ordinary screw-cutting tool the teeth of the cutter would remain in mesh with the screw without rotation. Between these two extremes any number of combinations of traverse and rotation may be found. In practice, a moderately slow traverse, slower than would be used in screw cutting, is combined with a rotary motion rather less than one tooth per revolution of the screw. In this way a screw is completely formed in a single traverse, the full depth of thread being removed in a series of thin cuts and the flanks being formed by the successive positions of the cutter as it rotates in mesh with the thread. Various thread outlines can be made by this process, which is capable of producing high quality threads in quantity, although it appears to be complicated from a description.

The Use of Die Heads in Screw Cutting

These tools depend on a frictional driving contact between the work and inclined faces on the die. There is no positive axial feed,

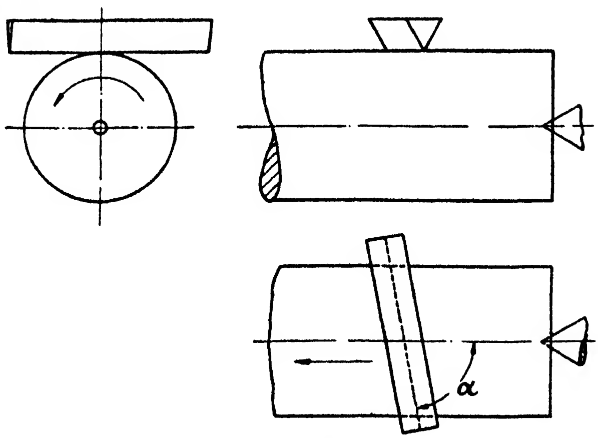


Fig. 158.

and the pitch of the thread cut by this method is likely to be less accurate on that account. The principle of action is shown in Fig. 158, wherein a piece of steel of triangular section is pressed on a revolving cylinder, being at the same time held at a constant angle α and allowed to slide freely from right to left. The lateral pressure on

the sliding bar is sufficient to traverse it sideways at a speed which depends upon the angle a. In the Whitworth three-part die stocks one of the dies is intended to act as guide to lead the dies on to the work at the correct speed for the pitch. It is cut at an angle equal to the thread angle at the full diameter, and makes contact over about one-quarter of the circumference. The other two dies are made with clearance so that they have effective cutting edges. With this pattern of die stock the thread is started by pressing the dies radially inwards with at least two or three threads on the guide die engaged with the work. In this way the thread is started squarely. These dies are used to take several cuts in order to reach the full depth of thread, and are commonly made to cut in both directions. The old style of die stocks had very inefficient cutting edges and cut very slowly.

The type of die head used in capstan and turret lathes is designed to cut the full thread in one cut. The dies are made with cutting rake and clearance to cut efficiently, and they must not be run backwards over the work. Hand die stocks are made to take the same kind of dies. Like the machine die heads they are fitted with a releasing motion so that the dies can be withdrawn to clear the work for removal. The tapered entrance or lead-on part of the dies reaches the full depth in a few threads and there is no difficulty on account of the varying angle of thread at different diameters. Each part of the die starts at the correct diameter, and there is quickly a full depth of thread to lead the dies on. When these dies are well made they produce extremely good threads both in form and pitch. The diameters are controllable by adjustment of the die heads. Screws up to any length can be made commercially by a modern die head within a tolerance on pitch of less than one-thousandth of an inch per inch. An important factor in controlling the pitch of the screws cut by this pattern of die-head is the exact setting of the dies so that each set of cutting edges is axially displaced with regard to the preceding one by a fraction of the pitch proportional to the angle between the cutting faces. This is of especial importance in this type of die-head because there is no wide guiding die as mentioned above in connection with the Whitworth three-part die stocks.

There is still a great variation in the tolerances adopted for screwed work. Several systems are in use, but many firms do not work within any specified limits for screwed work, even though they may have a limit gauge system for cylindrical parts. The explanation may be

found in the nature of a screw fit, which tends to hide defects. A thread may be thin and weak, but if its extreme diameter is up to size it may fit the corresponding nut without shake. Load, especially variable load, will very soon cause such a screw to work loose. Similarly a screw which is long or short in pitch may be made to engage a standard nut by reducing the effective diameter. It will appear to fit when fully engaged, although only the end threads will be in contact. When the screw is loaded the pressure will be concentrated on the end threads and they will be permanently deformed and will become slack in the nut.

Considerations as outlined above have led to the introduction of a truncated form of thread designed to limit the working contact to the flanks. Provision of clearance at the root and crest concentrates attention on the more important parts of the fit. It will not prevent a screw of faulty pitch from appearing to fit well when fully engaged, but it will help to make more obvious the gradual tightening as the nut is screwed on, which is characteristic of pitch errors.

Screw Pitch Measurement

For thread to thread measurements a special machine must be used. In this machine, the screw is mounted in a fixed position and a micrometer slide enables an indicator with a ball point to be traversed parallel to the axis of the screw. The ball point is engaged with each thread in turn and the position of the slide is read when the indicator registers zero at each engagement, that is, when the ball is centrally placed in the thread groove. A test of this kind is much more searching than the more usual one in which the pitch is found by measuring the displacement of a nut per revolution of the screw. Periodic errors occurring within the length of the nut do not affect its displacement and are not revealed, but the method gives the effective pitch of the combined screw and nut and is consequently all that is required for many purposes.

The pitch of screws used for fastenings may be checked by means of suitable " Go " and " Not Go " snap gauges when the effective diameter is gauged. The " Go " gauge is made to engage the flanks of the thread for a length of screw equal to the normal length of engagement with the nut. Thus the necessary reduction of effective diameter to compensate for pitch error is ensured. A " Not Go " snap gauge making contact with the flanks of one thread only, checks excessive reduction in effective diameter and consequently limits the pitch error to a permissible quantity.

CHAPTER XI

THE FORMATION OF SPECIAL OUTLINES

The standard machine tools are designed to generate surfaces by the combination of straight line and circular motions. Take, for instance, the lathe, which generates cylindrical, conical or plane surfaces by different combinations of a straight line with a circular motion. For these surfaces no special ratio between the rotary and the feed motions is necessary. It is, however, possible to connect the two motions so as to maintain a given ratio between them. Helical or spiral surfaces may then be generated, as in cutting screw threads or scrolls. The formation of screw threads in the lathe is well known; so is the use of the surfacing motion for turning a scroll. For the latter, the cross-feed screw is connected up to rotate with the main spindle in some definite ratio, for example to give one-quarter inch surfacing motion for each revolution of the work. A disc secured to the face plate would then have a spiral of one-quarter inch lead formed upon it.

Other machines having a slide rest, the milling machine, for instance, will generate one or more of the surfaces mentioned; but there are some surfaces, not so geometrically simple, which cannot be produced by the use of the ordinary feeds of machines with slide rests. Many of these more complex surfaces may be reproduced by means of a formed tool or template shaped to the required cross-section and caused to move in either a straight or circular path over the surface of the work.

When, as very often happens, a number of interchangeably similar pieces are to be machined to special forms not producible by the usual machine motions, the formed tool is of great value.

The making of such tools has been very much simplified by the development of the method of projection. By this method an enlarged drawing of the required outline is used to check the form of the tool, either directly by comparison with an enlarged image of the outline or indirectly by the production of a sheet metal template to be used for comparison with the tool.

The magnifications most often used in the projection method are ten, twenty and fifty, but one hundred is sometimes used. At fifty diameters it is possible to work within a tolerance of two ten-thousandths of an inch on the template or tool. This tolerance involves that the drawing shall be not more than one-hundredth of an inch in error, which requirement is not difficult to satisfy. Discrepancies between the drawing and the enlarged image of the template are easy to estimate within the same quantity. The method therefore succeeds in abolishing the principal trouble in the making of templates and formed tools, namely, the uncertainty as to where alterations are needed. It is not as a rule hard to make corrections if it is known just what is required and where. Many gauges and templates have been spoiled in course of manufacture by removal of metal in the wrong place through the lack of this knowledge. The projection method may be fairly considered one of the most valuable aids in the production of correct templates. In passing, it may be mentioned that arcs of very long radius, which are needed on account of the high magnification, may be drawn by plotting when they are beyond the range of a beam compass. The positions of points on a circular curve are calculated in terms of co-ordinates from two perpendicular base lines. When a sufficient number of points are known they are easily joined up by a smooth curve drawn by any of the well-known devices, as, for instance, french curves or one of the flexible strip appliances.

Non-Circular Curves

Calculation and plotting of points on a curve is very useful when the curve is not circular. Whether the curve is circular or not the large scale to which the work is done will minimise the errors, either in plotting or in selecting and drawing the smooth curve through the points.

In cases where the projection apparatus is not available, recourse must be made to one of the older methods of setting out and testing the template. Some of these methods are described below.

The first step is to set out the required form on the surface of a piece of sheet metal to the actual size. Straight lines are easy to draw with sufficient precision by the methods described in Chapter IV. Curves, especially when they are not circular, are rather more troublesome. The best way to deal with non-circular curves is to substitute for them arcs of circles. If the radius of the non-circular curve is

changing but slowly a single circular arc may be found which will approach it as closely as it can be made in practice. If the curvature changes more quickly several arcs of varying radius may be needed. These must be drawn carefully to merge imperceptibly one into another.

The process is less tedious than might be thought, because most of the curves encountered in shop practice can be drawn with very few arcs. The errors introduced by the use of a circle in place of a line of varying curvature are in any case likely to be less than that caused by other methods of setting out. One other method is to plot points on the curve by calculation and measurement but, though this may be done very accurately, the problem of connecting the plotted points with a smooth curve still remains. For this, curved templates could be used, but the result would not be any better than that obtainable from the use of circular arcs. Still another plan would also depend on carefully plotted points. The edge of the blank would be filed away until the points were reached. Provided a sufficiently large number of points were used, the smooth curve produced by skilful filing need not deviate appreciably from the curve required.

Each of the methods outlined above has its advantages under certain conditions, but the most used of the three is that of approximation by parts of circles. If the true curve is known the radii at various parts may be calculated and the deviation from the true curve of arcs drawn with these radii is then exactly known. If the deviations should be too great to satisfy the specified tolerances, intermediate radii must be found so that the length of arc drawn with each constant radius may be reduced. A well-known use of circular arcs for setting out special curves is that of the odontograph for setting out gear-tooth profiles. Strictly, these profiles should be involute or cycloidal in form, but many of them may be drawn with a single curve of constant radius. The remainder need several arcs.

In order to draw the arcs with the necessary precision some definite method of measurement is essential, as explained in Chapter IV. One method depends on a vernier gauge with marking points. Another depends on Johansson type blocks with a special point attachment. This has a conical point formed on a rectangular shank which is finished with one face exactly in line with the axis of the conical point (see Fig. 29b). The usual Johansson scribing point in conjunction with this centre point makes a divider which can be set

exactly to a given radius by means of distance blocks. Further details of methods of setting out are given in Chapter IV.

When templates must be very precise in form it is necessary to rely on overall measurements for the final adjustment and checking. The scribed line limits possible accuracy to a quantity but little less than its own width. Considerable ingenuity is needed to devise methods of checking an outline by means of measurements from a datum line or surface. Machines of the kind made by Alfred Herbert, Ltd., are very convenient for many purposes. In these machines a microscope with cross webs is carried on two horizontal slides perpendicular to each other. By the motions of these slides any part of the template may be brought under the intersection of the cross webs. Each position of the microscope and the motions necessary to reach it may be determined by readings of the micrometer screws on the slides. They may be read to 0·0001 inch. Certain jig-boring machines, for example, the Société Genevoise machine, are fitted with a microscope as an accessory. When this is mounted in place of a cutting tool the machine may be used as a measuring machine for checking work which has been machined or set out.

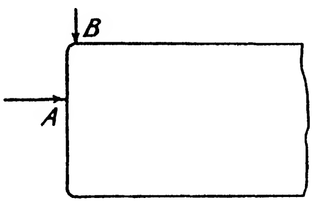


FIG. 159.

Although the travelling microscope as described has many uses and is able to give very reliable results under good conditions, it is dependent on the quality of the work. That is to say, a template might appear to be satisfactory under the microscope and yet be quite otherwise in use. The edge of a template is the important part when it is used in the ordinary way by observing the gap between it and a surface to be tested. But the edge may not be identical in form with the corner, as in Fig. 159, which shows an enlarged cross-section of the edge of a template, where the edge is slightly rounded. The microscope is most likely to be focussed on a point near B, which is not vertically above the working part of the edge A. Thus the readings obtained may not coincide with the actual form of the edge. This is a real difficulty in using the microscope, because corners, which appear to be quite sharp when viewed without aid, are found to be rounded when magnified. Doubt as to the surface on which to focus and some consequent fuzziness in the outline are troubles which diminish with practice in the use of the microscope. But

mechanics generally prefer measurements by contact such as can be made with the micrometer with the assistance sometimes of special contact pieces. The needles and prisms used in screw-gauge measurement are well-known examples of the intermediate contact pieces. They are used to reach parts which would be inaccessible to the simple micrometer. Generally speaking, they limit the surfaces of contact to small, definitely known areas.

In brief, it may be said that the outline of a template may be

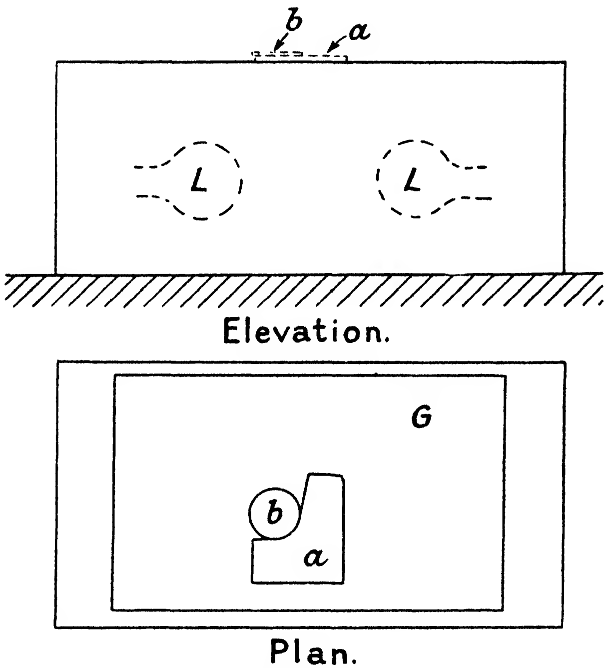


Fig. 160a.

marked out by a line, which may be drawn very accurately. But a line which may be used as a guide in making the template must be easily seen and may therefore be wider than the tolerance allowed. Although it is a very useful guide in the earlier stages of the work, it must be supplemented by other methods when the finished shape is approached. Such methods are either observations of the shape with a microscope fitted with cross-hairs, or, more usually, direct measurements from base lines with a micrometer and contact pieces.

When an outline has been formed to the approximately equivalent scribed circular arc, it may be tested by means of a thin disc turned

to the specified radius. The disc *b* and the outline *a* to be tested are placed in contact with each other on the upper surface of a frosted glass plate G, below which electric lamps L are disposed to give bright and uniform illumination. The arrangement is shown in Fig. 160a. It is generally known as a light box. When the two parts to be compared are fitted together over the lighted plate minute spaces between them are shown very definitely.

The discs used for testing curved outlines in this way are very easily turned to size. They are frequently useful for overall measurements in addition to their main purpose. Fig. 160b shows an example

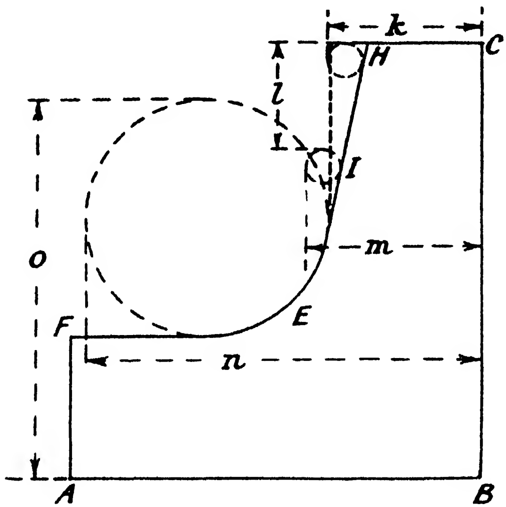


Fig. 160b.

of overall measurement by means of a disc. The gauge is made with the edges AB and BC straight and perpendicular to each other. The disc is turned to the diameter required and serves to check the circular part at E over the light box. It is also used to check the dimensions *o* and *n*. The position of the line FE is directly measurable as indicated. The remaining line HI may be tested in two ways. Two measurements over small cylinders will serve to determine points near each end. A straight edge will verify the remaining part. As an alternative, an angular slip may be applied as shown dotted in the same figure. This method is hardly worth while unless the same angle piece is applicable to several pieces, although once made it is very quickly used.

To illustrate the method of approximating to a curve of varying radius by means of circular arcs Fig. 161 has been drawn, which is an involute gear tooth template. Beginning at the base circle *ab* with a short radius, tangential to O*b*, which is progressively increased so that the arcs merge easily together, the final curve is not appreciably different from a true involute. In fact the errors which may arise in later stages are likely to be very much greater than those in setting out, especially if a lens be used. It is helpful to notice that in drawing the curve the tangents at the junctions of the arcs are almost in the same straight line.

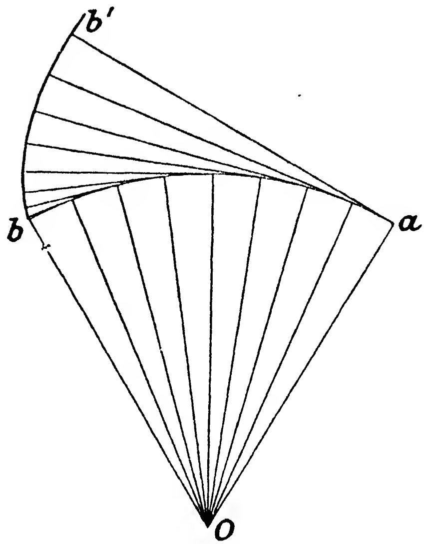


FIG. 161.

In a curve of this kind composed of so many arcs, the disc method of verification is not very useful. Probably the best way is to take measurements of the width at known depths with a gear tooth caliper of the kind made by the Brown and Sharpe Co. A vernier slide at right angles to the main vernier acts as a depth gauge. Since the widths might be correct even in an unsymmetrical template, symmetry must be ensured by making a second template for the half form. When this fits both sides of the original template and the transverse dimensions are also correct the form may be passed.

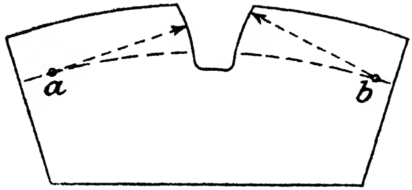


FIG. 162.

The above rather tedious process is only required for gear-tooth outlines in which the change of curvature is rapid, that is, for wheels of few teeth. With more than 30 teeth the involute curve differs very slightly from a circular arc in the length of a tooth. A case of this kind is shown in Fig. 162. The template is drawn with a

single arc from centres *a* and *b* on each side. A disc of suitable diameter attached to a straight edge so that the disc may be set tangentially to a radius of the template provides an easy method of checking the form of each side in turn.

It is advisable at this stage to remember that the elaborate processes outlined above have been very much simplified by the method of projection, which makes it possible to set out the required outline on a greatly enlarged scale. The method is, of course, dependent on uniformity of magnification of the image, but with the lens combinations now available this may be relied upon.

Formation of Outlines by Calculation and Milling

Special forms of larger size than those discussed above may be produced in a vertical spindle milling machine, or, if great precision is needed, in one of the jig-boring machines. It is assumed that the

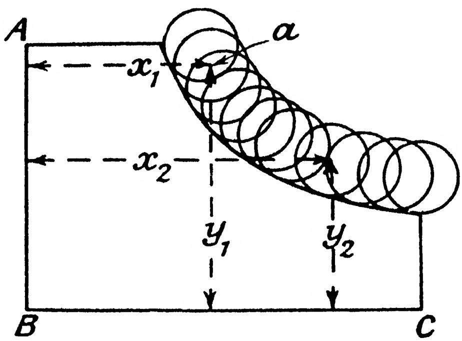


FIG. 163.

form is of such complexity that none of the simple mechanical movements found in machine tools will automatically produce it. An end mill is chosen, having an effective radius less than that of the sharpest curve in the given form. It is then necessary to imagine this end mill to be touching the required outline in several places (see Fig. 163). For each position of the end mill there is a centre point which can be found by calculation of the dimensions *x* and *y*. These positions are defined by reference to the two lines AB and BC. When sufficient points are known the blank can be machined by bringing the cutter up to the calculated positions in turn, which can be done very closely by the two micrometer feed motions on the table. If a sufficiently great number of positions are used, the result of the succession of cuts will be a very close approximation to

the desired surface, which will need but little hand finishing to smooth out the minute cross ridges. Even a comparatively few cuts will produce a surface which will be easy to finish by hand.

The effective radius of the cutter was mentioned in the description of the formation of a curve by a series of cuts with an end mill. By this, the radius of the circle actually cut by the end mill is intended. It is usually rather more than the radius of the end mill because there is some eccentricity in running.

Application of Template in Making Formed Tools and Cutters

As a rule the template is made as a means to an end, such as the making of a formed tool or cutter. In the latter case it is used as a gauge in filing a tool to shape. When it is likely that many similar

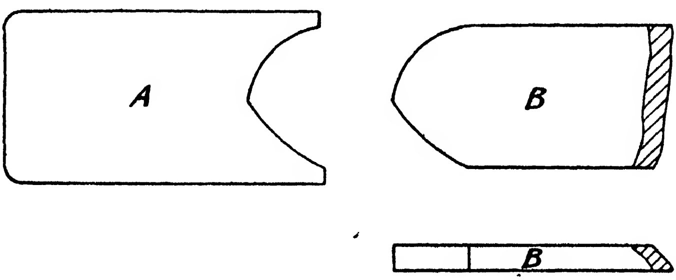


Fig. 164.

cutters will be required, an apparently elaborate process is adopted, which has the advantage that in case of renewals any stage can be repeated without loss of interchangeability. First a thin tool, B, one-eighth to half an inch thick, according to the stiffness necessary, which depends upon the size or length of the outline, is made to fit a gauge A, Fig. 164. This tool is filed to shape, hardened and tempered, and finally oil-stoned to correct any defects which may have arisen during the heat treatment. It is made with the end square with the cutting face, as drawn in Fig. 164, B. Since a clearance is necessary for cutting, the tool is set in the planing machine at an angle *a* to the direction of cutting. To prevent distortion of the outline of the tool planed it is set in a fixture at the same angle *a*. The diagram, Fig. 165, clearly shows how the correct form is reproduced and how the inclination of the tool B gives it clearance.

The tool C, which is to be used for backing off, or relieving, the cutter, is made of much thicker steel than the other tool B. It is

correctly shaped for the full depth, and may be ground on the top face without impairing the form, provided the ground surface remains parallel to the original face. Any change which occurs during the

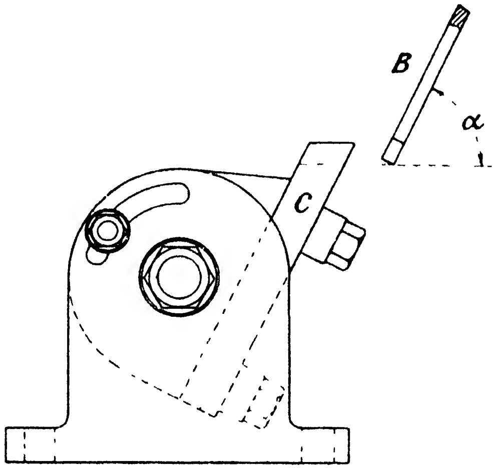


FIG. 165.

heat treatment of the tool B is rectified by oil-stoning, after comparison with the gauge.

The next stage in the production of the formed cutter is to mount the tool C in the tool-holder of the relieving lathe, which is a lathe with a cam-operated cross slide. The cutter blank, gashed and

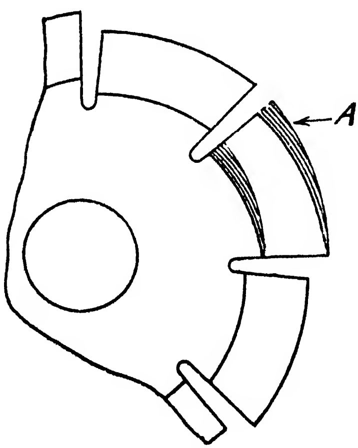


FIG. 166.

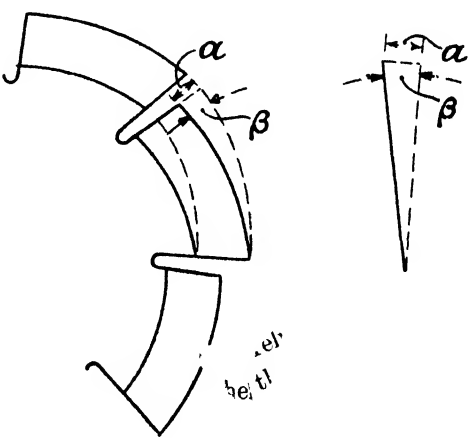


FIG. 167.

roughly formed as shown, is clamped on an arbor in the lathe. By means of a longitudinal shaft geared to the headstock the cross-slide cam is caused to rotate so that the cross slide is drawn towards the centre of the lathe as each tooth of the blank passes the tool. When the tool is opposite a space in the blank the cross slide is drawn quickly backwards by a spring. Thus by a succession of cuts the teeth are given a spiral form (see Fig. 166).

There are differences in the mechanisms of relieving lathes built by various makers, but the principle of action of them all is substantially as described. An important item to the user is the choice of cam for any particular job. This depends upon three factors, namely, the clearance angle required, the diameter of the cutter, and the number of teeth. These are related by the expression (see Fig. 167) :—

$$a=\frac{\pi d}{n}\cdot\tan\beta$$

where β=clearance angle
a=rise of cam
d=diameter of cutter
n=number of teeth.

Clearance of Formed Tools and Cutters

The clearance angle β must be greater than is used for an ordinary cutter because it is merely a nominal value, which applies only to parts of the edge which are parallel to the axis of the cutter. It is obviously impossible to produce any clearance by an inward motion of the forming tool on a surface which is perpendicular to the axis of the cutter. This is explained in Fig. 168, where the true clearances at A and B are shown by the angles α_1 and α_2. Nominal clearance angles may vary from 6° or 7° in cutters with the edge almost parallel to the axis, up to 15° when the edge approaches the perpendicular. Clearances much greater than 15° are not often used because the nominal clearance of the cutter is only about half that of the formed tool with which the cutter is relieved. That follows because the surface from which the effective clearance is measured is inclined to the vertical (see Fig. 169). Therefore the nominal clearance given to the relieving tool may be 25° or 30°. It is, in extreme cases, limited by the ability of the tool to hold an edge of more acute angle, rather than because the clearance is sufficient. In formed tools and cutters having edges nearly perpendicular to the axis of

rotation the clearance is rarely sufficient. This is easily seen by examination of a milling cutter for involute gear-wheels of less than,

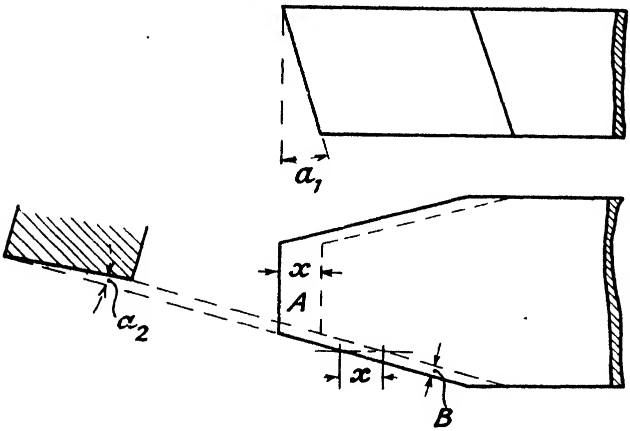


FIG. 168.

say, twenty teeth. The sides of the cutter teeth are always rubbed for some distance behind the edge if the cutter has had much use.

The tool shown in Fig. 168 gives an example of the variation of clearance at different parts of the cutting edge. This tool is of the acme thread form and would be used to relieve a hob. On the inclined sides, as at B, the clearance angle is 6° measured from a vertical reference pane. It is only 3° measured from the tangent plane to the spiral surface of the cutter. But in order to get this clearance on the inclined sides the value on the part A parallel to the axis is 17° from the vertical plane, although its value with reference to the tangent plane to the cutter is much less.

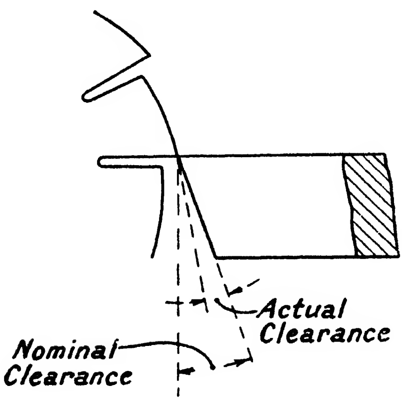


FIG. 169.

Formed cutters and the tools used for relieving them are not often made with rake, that is to say, the cutters are ground radially and the tools are ground so that when they are set in the backing-off lathe the ground face will be horizontal. Formed tools used for repetition

turning in capstan and automatic lathes are sometimes made without rake, but they are found to cut more easily and cleanly if rake is given. The influence of rake on the form of the tool must be considered, and due allowance made so that the work may be of the specified shape.

Correction of Tools for Clearance and Rake

There are two main classes of formed tools, straight and circular, shown in Fig. 170, A and B respectively. If they have clearance

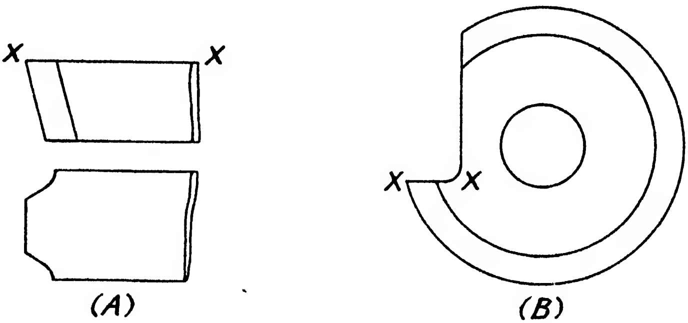


FIG. 170.

but no top rake they should be made so that the section on plane XX is similar to the outline of the product required. One method applicable to straight form tools has already been described. For circular form tools the method shown in Fig. 171 is convenient. The desired section is turned at the plane YY, below centre, either by means of a tool filed to shape or by means of a single point tool moved in the specified path by the micrometer feed dials on the slide rest. An alternative method of reproducing a given outline is to prepare a template and, after setting it horizontally in a fixed position on the lathe, to trace round it by means of an indicator attached

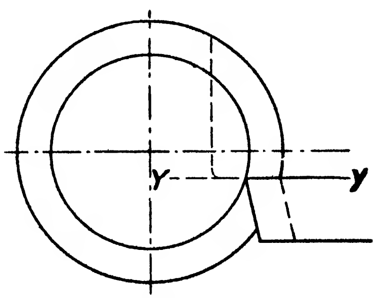


FIG. 171.

to the tool rest (Fig. 172). If the indicator reading is kept constant the tool in the same holder will be caused to follow the path defined by the template.

To obtain a given clearance by setting the tool below centre the following calculation is useful :—

$$h = r \sin \beta$$

where h=depth of tool below centres

r=extreme radius of circular formed tool

β=clearance angle required.

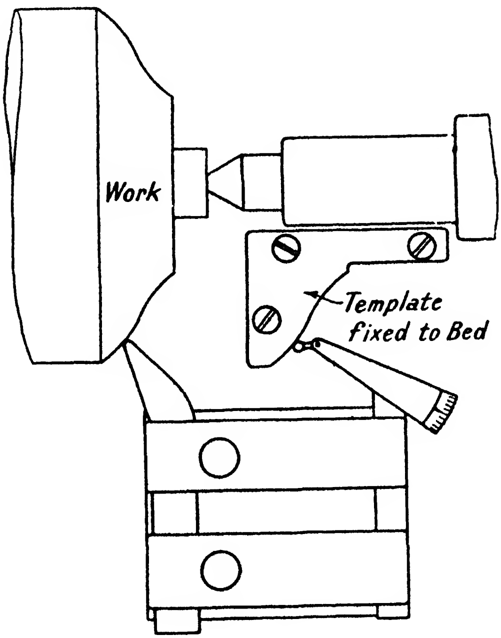


FIG. 172.

The diagram shows that the clearance will vary with the radius of the parts of the cutting edge, becoming greater as the radius becomes less (Fig. 173).

When allowance for clearance is made in the way described the outline of the work is produced on the section AB, which becomes the radial section of the work turned.

Rake and clearance together cannot be compensated for by this simple mechanical device, because, when rake is given to a tool, the top surface of the tool is no longer like a radial section of the work. Referring to Fig. 174, the following simplified expressions for straight formed tools with rake will give approximate results which are easily within the limits of error of the machining process :—

Let a=clearance angle
β=top rake
r_1=maximum radius of work
r_2=radius at root of form on work
f=depth of form on cross-section of straight-formed tool

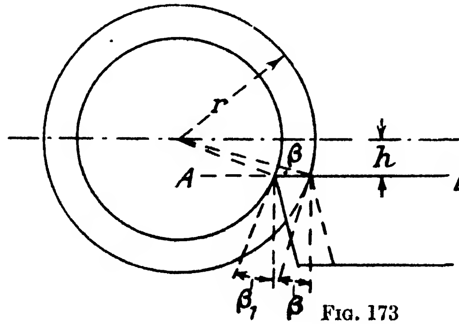


FIG. 173

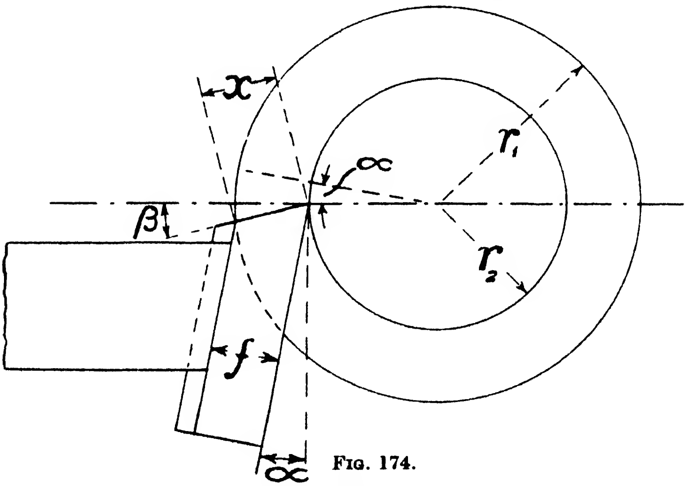


FIG. 174.

Referring to Fig. 174, the dimension " x " of the top face of the tool is found from the expression :—

$$x=\sqrt{r_2^2 \cos^2\beta+r_1^2-r_2^2}-r_2 \cos\beta$$

Then, $$f=x \, . \cos(a+\beta).$$

For a circular formed tool with rake, as shown in Fig. 175, the calculation is a little different, as follows :—

Let a_1=clearance at maximum diameter of the formed tool
a_2=clearance at minimum diameter of the formed tool
r_1 and r_2=maximum and minimum radii of work respectively

R_1 and R_2=maximum and minimum radii of the formed tool
β=top rake of tool,

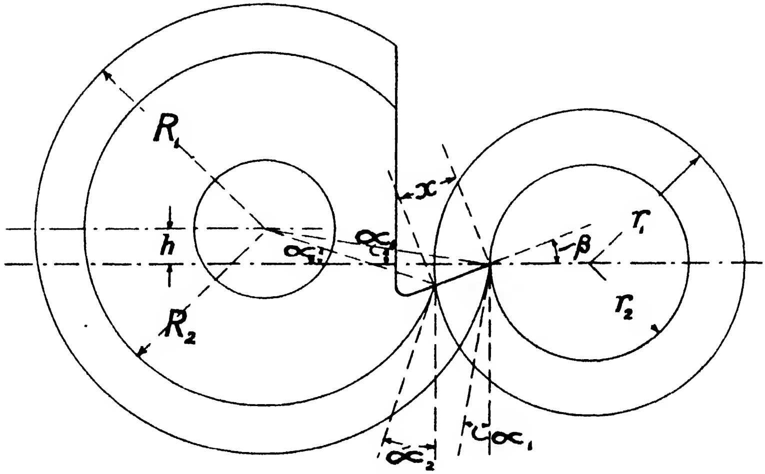


FIG. 175.

Then, as for the straight-formed tool with rake, the dimension "x" of the top face of the tool is

$$x=\sqrt{r_2{}^2\cos^2\beta+r_1{}^2-r_2{}^2}-r_2\cos\beta.$$

Whence, $R_2{}^2=[R_1-x\,.\cos(\beta+\alpha_1)]^2+x^2\sin^2(\beta+\alpha_1)$

and $\quad R_2=\sqrt{[R_1-x\,.\cos(\beta+\alpha_1)]^2+x^2\,.\sin^2(\beta+\alpha_1)}.$

The foregoing expressions should be applied to find the corrected depth of form at all points where the outline of the edge changes direction.

Precision Grinding of Formed Tools

The formed tool should be trued after hardening to the corrected outlines found as described above, but oil-stoning to a template is a tedious process for a straight formed tool and is almost beyond possibility for a circular formed tool. Consequently these tools were always a source of doubt so long as reliance was placed on allowance for change of shape in hardening with a possibility of making only very small adjustments by stoning afterwards. Even with a steel whose behaviour is well known there may be variations from time to time which will make the most careful estimate incorrect. This element of uncertainty may easily upset estimates of cost and, what is sometimes even more important, promises for delivery. It is to be expected therefore that the process of grinding developed by the

Brown and Sharpe Co. should find increasing use in finishing formed tools to size after hardening. Applied in the beginning to the more exacting cases, where the tolerances were too fine to permit success by hit-and-miss methods, it has been extended to all formed tools by some firms. Even for comparatively generous tolerances it is not necessarily more costly than the older methods, especially in the case of a firm using many formed tools. In such a case the cost of wheel formation may be very small, because a fairly large stock of wheels will be kept, and it will not often be found necessary to alter the shape of a wheel very seriously, since there will usually be a fairly good approximation to the required form in stock. Thus one of the chief sources of expense, namely, wheel wastage, is greatly reduced. There is, in addition, a positive saving in the early stages of formed tool manufacture when the tools are to be finished by grinding, since wide tolerances can be permitted in the preliminary formation. This may go far to compensate for the cost of grinding.

When the use of the wheel is thoroughly understood, it is possible to produce an intricate form by grinding with an accuracy which cannot be approached by other methods. Bearing in mind the irregular surface of the wheel and the fact that there must be some wheel wastage in the grinding process, it seems at first that extreme accuracy would not be possible. But when the wheel is used carefully the loss of size by wheel wastage is almost negligible for quite long periods of use, otherwise it would not be possible to grind from one end of a long cylindrical bar or shaft to the other without appreciable change in diameter, irrespective of the direction of feed

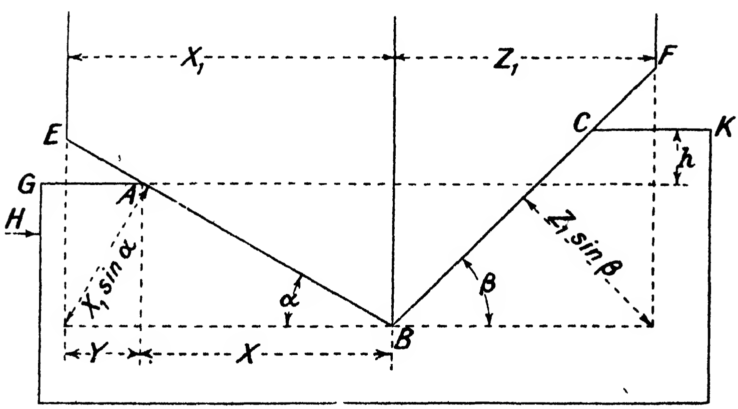


FIG. 176.

and without in-feed during any one traverse. Yet it is well known that this is a regular daily occurrence in thousands of shops.

With regard to the other point, namely, the apparent roughness of the surface of the wheel and the impossibility of taking any fine measurements from so variable a quantity, it must be remembered that the effective surface of a wheel in use is really generated by the almost infinite number of grain points or cutting edges. Each of these edges traces out a very narrow but complete cylindrical surface. There are so many of them that the narrow cylindrical surfaces overlap, and the result is a complete cylinder of the full width of the wheel when the wheel is in motion. The original cylinder is formed by traversing a diamond slowly past a rotating wheel along a path parallel to the axis of the wheel. But the path of the diamond may be varied so that conical surfaces, or surfaces curved in cross-section, may be generated.

In any case, the number of cutting points on the wheel which lie on the outer surface is so great that the wheel behaves as though the points were continuous cutting edges from one side of the wheel to the other. When the wheel, which has been formed in this way, is applied to a piece of steel such as a roughed-out form tool, it will reproduce the path of the trueing diamond in cross-section on the steel.

The process is therefore to cause a diamond point to trace out a path which is the same as the cross-sectional outline of the formed tool. This is done in such relation to a grinding wheel that all parts of the wheel encroaching beyond the path of the diamond are removed. The wheel, then, has a surface of the desired shape and consisting of extremely sharp cutting points. Provided it is used with care the formed wheel will grind away a very considerable quantity of steel before the surface begins to lose its form to any appreciable extent. As an example of the method, consider a tool of the cross-section shown in Fig. 176. The two plane surfaces terminating in the lines AB and

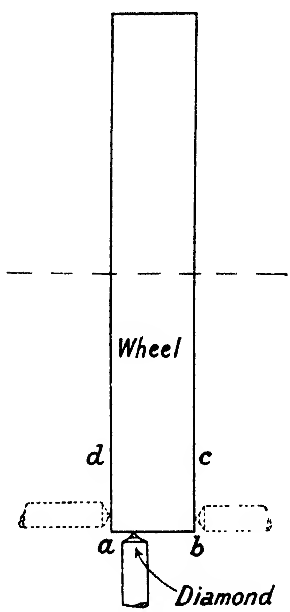


FIG. 177.

BC in cross-section are required to intersect in a line passing through the point B. It would not be possible to ensure this by grinding the two surfaces separately. Although the angles could be produced, the line of meeting would be indefinite in position. The roughed out and hardened tool having been set with its cross-section parallel to the axis of the wheel, the parallel surfaces GA and CK would first be ground so that the dimension *h* would be correct. Then the wheel would be formed to grind the surfaces AB and BC. The precautions taken to ensure the correct position of the point A are described below.

Starting with the axis of the wheel parallel to the direction of traverse the diamond is first traversed along *ab*, and then by means of the cross slide perpendicularly along *bc* and *ad* (Fig. 177). By using the radius forming holder described on p. 214, Fig. 179, with the point of the diamond set on the vertical axis the diamond may be used to cut on either face *ad* or *bc* without changing the position of the point with regard to the table of the machine. It is possible therefore to make the distance *ab* a definitely known quantity, by taking the difference of the readings of the micrometer feed when the surfaces *ad* and *bc* are finished.

Assume a distance X_1, slightly in excess of X, so that the sloping face BE of the wheel may slightly overlap the part AB of the tool. Then after turning the axis of the wheel through an angle a, by means of the graduated base of the head, the diamond holder is set at right angles to the traverse direction of the table, well out of contact with the wheel. The diamond is next traversed slowly to and fro and very carefully fed in towards the wheel, until the sound indicates that very slight contact is made at point *a* of Fig. 177. The in-feed dial reading is noted at this point, and the feed is continued until the initial reading is increased by $X_1 \sin a$.

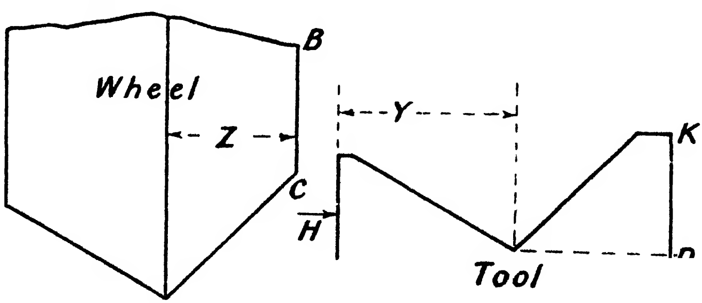


Fig. 178.

The same process is repeated for the side BF after setting the wheel at an angle β to the direction of the table traverse. For this face the in-feed is continued for a distance $Z_1 \sin \beta$ after first slight contact of the diamond with the corner of the wheel, Z_1 being equal to the width of the wheel minus X_1.

Finally, the wheel is set with the axis parallel to the table, in readiness to finish the two sloping surfaces of the tool. It is at this point that the great convenience of the method becomes apparent, for, by the process of formation the position of the intersection of the two conical surfaces is definitely known with regard to the trued sides of the wheel. This face enables the point B, Fig. 176, to be fixed with very great precision. One side face, BC, Fig. 178, of the wheel is brought very lightly into contact with the side H of the tool, and the reading of the traverse dial is noted. The wheel is then withdrawn from the tool by the cross slide and is moved sideways through a distance Y+Z (see Fig. 178). During this lateral traverse the extreme edge of the wheel is lightly touched on the face GA, Fig. 176, of the tool. This will give a zero reading from which the depth of the point B may be obtained. When the wheel is in position laterally it is only necessary to feed in the required depth, while the tool is traversed vertically up and down past the wheel in order to finish the sloping surfaces in the specified position on the tool. Given reasonable care in the details of the operation, the precision which may be obtained by this method is very high and is not to be exceeded by any other method of finishing formed tools.

In the example taken, the surfaces GA and CK at the sides of the vee are easily finished either to the same height or to different heights as may be required, and any other combination of plane surfaces may be finished by repeated application of the method outlined.

Since circular arcs are common forms in the outlines of formed tools it is desirable to have a ready means of forming a wheel to grind them. A radius forming fixture is shown in Fig. 177, which is adaptable to form convex or concave curves as the diamond is behind or in advance of the axis. The exact position of the diamond is determined by the use of spacing blocks or gauges (Fig. 179, A), designed to slip over the shank of the setting gauge. One of these is of such thickness that it will cause the extreme point of the diamond to lie in the axis of rotation XX of the fixture. This particular distance piece is the one which would be used to true the sides *ad* and *bc* of the wheel (Fig. 177), to leave a definitely known thickness

between them. With this distance piece in use, the diamond may be faced in any direction and the position of the working point will

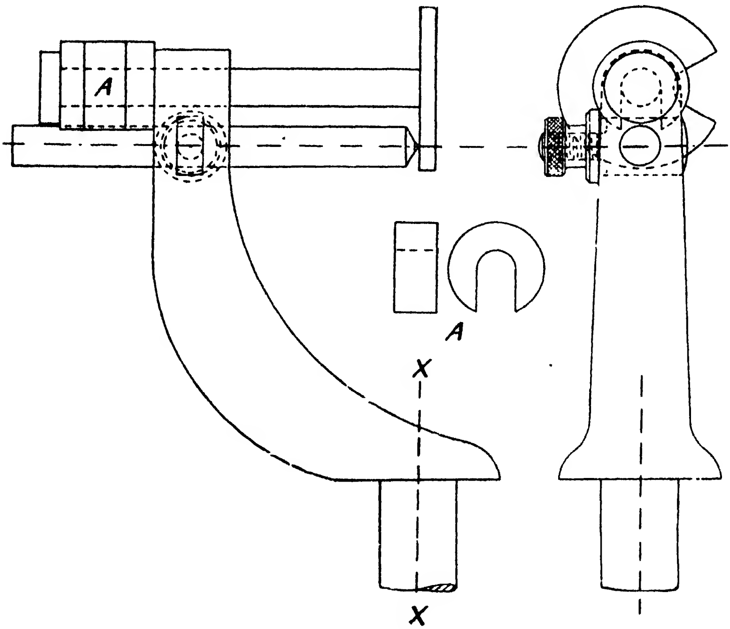


FIG. 179.

remain unchanged. The distance between points *a* and *b*, Fig. 177, will therefore depend only upon the traverse and may be read off the micrometer feed dial.

The radius attachment may be used in a number of ways. For

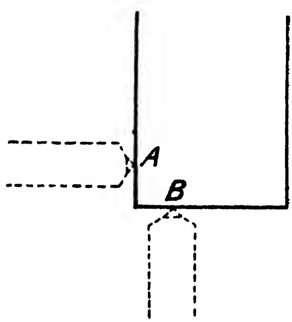


FIG. 180a.

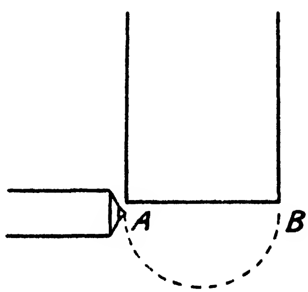


FIG. 180b.

example, it may be used to form the edge of a wheel to a semicircular

cross-section of the known width. If the wheel is slightly thicker than the required semicircle, it should first be reduced to the correct thickness. The diamond is set behind centre by inserting a distance piece equal to the specified radius in Fig. 180. The diamond is placed in position with the holder parallel to the axis of the wheel and is traversed until it makes very light contact at A, Fig. 180a. At this point the reading of the longitudinal feed dial is noted. Contact is next made at point B with the diamond at right angles to its first position, and the cross-feed reading noted. This reading is used to determine when the full curve has been generated, and to avoid needless loss in formation. Using the traverse reading already noted the diamond is set as at A, Fig. 180b, in line with the side of the wheel but well away from it. This traverse position should remain unchanged throughout the formation of the wheel, which is done by feeding the diamond slowly towards the wheel and at the same time swinging it horizontally to and fro between A and B, 180° apart. When the cross-feed dial indicates the predetermined reading the semicircle should be complete.

In a similar way, a quarter circle can be formed to merge two surfaces at right angles, but in this case the angular motion of the diamond must be limited to 90°. Other applications may easily be worked out.

The curves discussed above have been convex on the wheel, but it is quite possible to generate concave edges on the wheel. The extent of the curve must obviously be rather limited when it is concave, since the diamond holder must be kept clear. Otherwise there is little difficulty, the only difference being that the distance pieces are of such thickness that the diamond may project beyond the axis a distance equal to the radius desired.

The formation of the face of a grinding wheel to a combination of straight lines and circular arcs, as described above, covers a great deal of formed tool work. For less simple shapes there is a forming attachment in which the path of the diamond across the face of the wheel is controlled by a template. The template must be made to the corrected form as discussed on p. **206**, because the radial section of the grinding wheel will be similar to the section of the cutting tool by a plane perpendicular to the clearance face. The outline of the work to be turned will be produced by an oblique section of the formed tool. When setting out the template it must be regarded as a cam acting on a roller of some selected diameter. The diamond point which acts on the abrasive wheel is of very small dimensions,

consequently the template must be modified to make allowance for the difference in radii of the roller and the diamond point. This is a geometrical problem which need not be discussed here.

When the wheel has been formed it may be used for either straight or circular-type formed tools. The difference is merely a question of the method of moving the tool past the wheel, that is, whether it moves in a straight or in a circular path.

It must not be expected that a wheel with a relatively deep form can be worked at quite the same rate of production as a plain parallel wheel. The variations in diameter, and consequently in surface speed, will obviously make it impossible for ideal conditions to exist across the whole face of the wheel. But usually the main object sought in using the formed wheel is to generate surfaces of special shape. Speed of output is in such cases secondary to the need for precision.

There is now available a very ingeniously designed machine, made by Loewe-Gesfürel A. G., which enables templates or formed tools to be ground to any shape from a fifty times enlarged drawing. The method adopted is to cause the intersection of the crossed webs of a microscope to trace out step by step the desired outline. Meanwhile the template is observed by means of the microscope, and a grinding wheel is applied to it until at each point in turn the edge is ground away to coincide with the meeting point of the crossed webs. By a sufficient number of repetitions of the process, the whole of the form is reproduced on the template. The microscope is mounted on a pantograph so that it follows on a small scale the motion of a tracing point which is caused to trace round the fifty times enlarged drawing. In this way the position of the microscope is very exactly controlled. Taking into account the possible errors in the drawing and in the location of the tracing point, it is possible to place the microscope within two ten-thousandths of an inch of the correct position, and by careful use of the grinding wheel the outline should be ground to a tolerance not exceeding that amount. The wheel head is mounted on a compound slide rest permitting the wheel to be placed as required in the horizontal plane. In addition to these adjustments there is an automatic vertical motion of the wheel, which enables it to grind a depth of nearly 2 inches. This vertical reciprocation is variable so that any thickness of work from a thin template up to a formed tool nearly 2 inches thick may be ground. When it is desired to grind a circular-formed tool the vertical motion is not used, but instead the tool is mounted on centres on a special fixture and is rotated past

the wheel which is placed at centre height, otherwise the tool is not moved during the process of formation.

In the description just given the motion of the wheel is referred to as vertical. That is the normal setting, but it may be varied 10° from the vertical in any direction. By this means formed tools may be ground with suitable clearance.

A wheel forming attachment is fitted to the machine so that the edges of the thin disc wheels may be formed to suit the profiles to be ground. The object of forming the wheel is to ensure that contact shall take place at one point of the edge only, or rather, that no part of the wheel shall encroach beyond the correct outline when the wheel approaches the crossed webs. For example, when grinding a curved outline the edge of the wheel must be formed to a shorter radius than that of the curve to be ground. Curves down to 0·004 inch can be ground with suitable fine grained wheels.

CHAPTER XII

MEASUREMENT OF GEAR-TOOTH ELEMENTS AND RESULTS OBTAINED BY VARIOUS METHODS OF CUTTING AND FINISHING

A FULL treatment of the subject of toothed gearing would require several volumes. It is hopeless to attempt a complete discussion within the limits of a single chapter, and in any case many valuable books are already available which deal with various phases of the problem. In this chapter an attempt will be made to describe some of the recent developments in the production of high-quality gear teeth and the devices used in measuring and gauging them.

Choice of Tooth Profile

There are many curves which would be geometrically suitable for the profiles of gear teeth. Several groups of curves have been proposed and used at various times in the history of gearing, but the involute has gradually become established and is now almost the only one used. This is partly due to the latitude which it permits in regard to centre distances. Two involute gear-wheels will mesh together and work perfectly over a considerable range of centre distances. There will be rather more backlash at the longer centres, but otherwise the action will be quite correct.

Another reason for the survival of the involute form of tooth is constructional. The involute is easily reproduced by simple and robust mechanisms.

There are two principal methods used in the formation of gear teeth. These are known as the copying and the generating processes. The copying process depends upon the existence of the particular profile which is to be reproduced on the teeth. This copy may be embodied in a formed tool or a formed milling cutter, or it may be a template which is used to guide a single point tool round each tooth face in turn.

Principles of Tooth Formation

The other principal method of tooth formation does not entail the use of a copy of the tooth to be produced. It depends upon the generation of the desired profile by the use of a particular tool and a special combination of feed motions. The feed motions may be imagined if one thinks of the blank to be cut and the cutting tool as two members of a train of toothed gearing. The blank and the tool are then to be moved as though the blank were a finished gear meshing correctly with the other gear represented by the cutting tool. That is to say, the blank and the tool are caused to roll together. At the same time the tool is given a cutting motion perpendicular to that by which it rolls in mesh with the blank. Thus as the two roll slowly into mesh the spaces between the teeth of the blank are gradually cut away and the outlines of the teeth are shaped.

It is a great advantage of the generating process that only one cutter is required for all wheels of each pitch and angle, irrespective of the number of teeth in the wheels. For example, a rack form cutter of eight diametral pitch will cut wheels of all sizes from 1 inch up to 25 inches or more. Teeth will be formed on each particular size of blank of the curvature peculiar to that diameter. None of these teeth will be like the original rack teeth used as a cutter.

Errors in Gear Teeth

Each method of making gear teeth has its own peculiar advantages and its own defects. It may seem that undue prominence is given to the possible defects in gearing. But the conditions under which many gear-wheels work are such as to direct attention to very minute faults—faults small enough to escape notice entirely in other machine components. Gear wheels are judged by the noise they make. The difference in dimensions between a noisy gear and a quiet gear is often no more than two or three ten-thousandths of an inch. When the intricate shape which must be made within this narrow limit is remembered, the difficulty of making silent gears may be realised. If the gears could be left in the soft state as cut the problem would be easier, but the loads and speeds now specified necessitate hardened wheels.

Tests on gear teeth before and after hardening show that a wheel of quite satisfactory accuracy in the soft state is rarely so good after heat treatment. H. F. L. Orcutt remarks that very few hardened gear-wheels will clean up all over the teeth with a grinding allowance

of three-thousandths of an inch. The process of hardening appears to develop all the hidden defects in the steel. Teeth originally straight and true become twisted. Carefully formed surfaces become warped.

Just as in other applications of hardened steel, it is coming to be realised in the case of gearing that accurate results can only be achieved with certainty by grinding. It may be remarked in passing that grinding will not in all cases ensure quiet running gears, even though the grinding be done with all possible care. Sometimes all the other factors concerned with the gearing must be examined before silent running is secured. The features of good toothed wheels are as follows :—

1. Uniformity of pitch.
2. Correct tooth profiles.
3. Teeth truly aligned with the axis of the wheel.
4. Teeth symmetrical about radii.
5. Concentricity of teeth with axis.
6. Smooth tooth surfaces.

The pitch of the teeth in a gear wheel is dependent on the index wheel in the gear-cutting machine. It is one of the most important factors in the manufacture of quiet gearing. When the teeth are made by a formed cutter or formed tool the duty of the index wheel is comparatively light. The blanks are indexed one tooth between cuts and are then clamped in position for the next cut, thus the index wheel is relieved of load when it has located the work in the correct position. The design of the clamp must be of a kind to avoid moving the work as it is tightened. The wheel is not subject to appreciable wear and should retain its truth almost indefinitely. In regular gear-cutting machines the dividing wheel is usually made of greater diameter than the largest work it is intended to index. The errors in the wheel are thereby reduced in the ratio of the diameters of the dividing wheel and the work.

Given a satisfactory dividing wheel, errors may still arise in spacing the teeth in the work because the machine is not rigid or because the work is rushed unduly and so is caused to heat unevenly. The device known as block indexing is used to distribute the heat round the whole rim of a wheel. Instead of indexing one tooth at a time several teeth are taken so that one space is cut and several are missed regularly round the wheel. Thus the heat of cutting is spread round the wheel and no unequal expansion is caused. The easiest way is

to select some number which is not a sub-multiple of the number of teeth in the wheel and to index so many teeth at once. After a number of revolutions of this process all the teeth will be cut. Suppose a blank is to have fifty-four teeth cut in it. Select five for block indexing. After ten operations the fifty-first space will be reached, and at the next operation the cutter will reach the fifty-sixth space. All the teeth will be cut during five revolutions of the blanks, and the temperature of the blanks will be kept nearly uniform all over.

In machines working on the generating principle the dividing motion is an essential feature of the generating process. The blank is steadily rotated while the cutter receives a corresponding motion, either rotation or traverse. Both these motions must be accurate, because any fault will affect the spacing of the teeth and the tooth form. There are three distinct mechanisms used in gear-generating machines. In the gear-hobbing machine the rotation of the hob gives a lateral motion to the hob teeth which is equivalent to the steady traverse of a rack parallel to the axis of the hob. This is easily understood by holding a screw up towards a lighted window and watching the thread profile as the screw is slowly turned. The blank is positively driven by gearing from the hob spindle, so that the blank moves through one tooth as the hob rotates once, if the hob is single threaded; otherwise the blank is moved as many teeth per revolution of the hob as there are threads in the hob. The rotary motion of the hob provides the cutting motion. The indexing motion is continuous and takes place under load. This is urged as an objection to the hobbing process, but if the parts are suitably designed there is no reason why they should not give a fair length of life and, in practice, they do give quite good results. Quality of output depends upon the truth of the index wheel and worm, upon the hob, and to a less extent upon the intermediate gearing. Form ground hobs are now commonly used for the better work.

The universal milling machine may be adapted with very little trouble to act as a hobbing machine. A spiral gear or other right angle drive from the cutter spindle to the spiral head provides the necessary rotation of the blank through the ordinary change wheels of the spiral head. The principal difficulty is the feed motion, which is rarely slow enough on the ordinary machine to give a well-finished tooth. It is, however, possible to use a hand feed with a little care. When obtaining hobs for cutting spur wheels the fact must be mentioned, as the pitch is measured differently in hobs for spur gears

and for worm gears. The pitch of a spur gear hob is measured at right angles to the thread at the pitch surface. For worm gearing the pitch of the hob is measured in a direction parallel to the axis. The distinction arises from the different methods of setting the two kinds of hob. The thread of a spur-gear hob must lie parallel to the axis of the blanks, that is, the axis of the hob is not quite square with the axis of the blanks. Worm-gear hobs, on the other hand, are set square with the blanks to be hobbed. The difference between the two kinds of hob is not very conspicuous in single-threaded hobs of fine pitch but increases with the pitch and the number of threads.

In the Fellows type of gear generator, using formed cutters like a gear-wheel with axial clearance, both the cutter and the work are continuously rotated during the shaping process. There are two dividing worm-wheels connected by gearing. One rotates the cutter and the other rotates the work. Their accuracy very largely determines the quality of the work, both in regard to equality of spacing and also in regard to outline.

The rack type of generating machine depends upon the indexing motion in conjunction with a longitudinal traverse of the rack. These motions together with the rack tool determine the indexing and form of the teeth.

Permissible Pitch Error

In all gear-cutting operations the accuracy of the index wheel is fundamental, and according to Orcutt * the preparation of a sufficiently accurate index wheel was one of the most difficult tasks in the development of the gear-grinding process. The standard which Orcutt ultimately found satisfactory was correct within two seconds of arc, which is equivalent to 0·00012 inch at a radius of 12 inches.

The importance of a small limit of error in indexing may be imagined when a design involves contact between two or more pairs of teeth at once. If a tooth is very slightly out of pitch the whole load must be taken on adjacent teeth. It is doubtful if, in a large proportion of ordinary cut gearing, there is ever more than one pair of teeth in effective contact. Although this may be tolerated for moderate loads and relatively low speeds, it is essential that gears loaded to their full capacity should be so precisely formed that driving contact shall exist between several pairs of teeth simultaneously, as assumed.

* "Ground Gears" (Discussion), H. F. L. Orcutt, Proc. I. Mech. E. 1925, Vol. II.

Pitch errors in the wheel-cutting machines have been masked by the much greater errors introduced during heat treatment. For instance, a typical gear before hardening had a maximum pitch error of 0·0008 inch. The same gear after hardening had errors in pitch of three times that quantity.

After pitch, the tooth profile is important. This depends in the copying process, first on the quality of the formed tool or template used, and second on the rigidity of the machine used in cutting. It is assumed that the machine is set correctly, otherwise a correct cutter may cut a tooth which is off centre and is therefore not symmetrical about a radius. A test for correct centring is shown in Fig. 181. After setting the cutter as nearly central as can be judged,

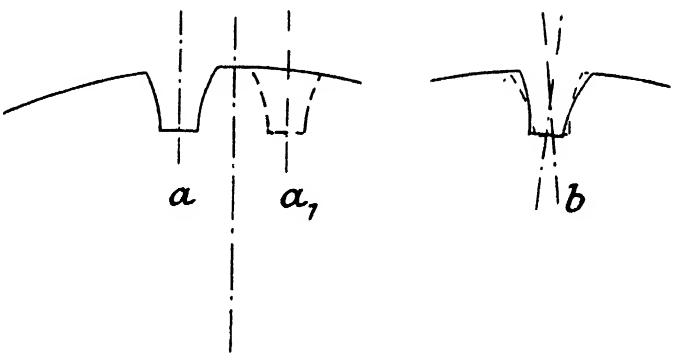


FIG. 181.

a dummy blank, B, is mounted on a mandrel on centres and a cut is taken through as shown in Fig. 181, *a*. The blank is then turned end for end after coating the notch with copper sulphate. The effect, if the cutter was not set centrally, is shown in Fig. 181, *b*. A cut in this position will remove the copper at diagonally opposite points. If the cutter had been originally central the cutter would pass through in the second position without marking the copper unevenly.

Another fault in setting may result in the teeth being cut out of line with the axis. This would arise from wrong setting of the machine table. It is serious in its effect on the gears, as it concentrates the load at one end of the teeth, causing heavy wear and risk of breakage. Ordinary care should eliminate this source of error in soft gears, but it is very liable to be developed in hardening.

The milling cutters used in cutting gear teeth can be made accurate

to form within a tolerance of $\pm 0{\cdot}00015$ up to the stage where they are hardened. It is hardly possible to form-grind these cutters. Hence their final quality depends upon the absence of distortion during hardening. The cutters are made in large quantities, and the firms who make them are able, by rigid control throughout, to produce astonishingly good and consistent results. For especially good work it is possible to obtain almost perfect cutters by selection from large stocks.

Standard formed cutters are made to cover a range of diameters and cannot therefore be exactly right throughout the range. Each cutter is made to be correct for the smallest wheel of its range. For all the other sizes it cuts a form which is rather too sharply curved. This tends to reduce the effective length of tooth face and so reduces the arc of engagement, but only takes place to a very small extent.

The errors which are found in the gears cut in generating machines are usually traceable to lack of rigidity in the machine or to faults in the generating motions. These will affect both the tooth spacing and form. The tools used in this class of machine are capable of being form-ground after the hardening process. They can therefore be eliminated as a source of error. It must be admitted that many hobs are used without being form-ground, but this is merely in cases where the specification does not justify the additional cost of grinding. There is no insuperable practical difficulty in the production of form-ground hobs.

Gear Grinding

It is now hardly disputed that grinding is essential for the finishing of hardened gears which are to satisfy the more severe specifications. Even with the greatest care in the selection and preparation of material and in the manufacture of the gears, some distortion takes place in heat treatment. It is especially noticeable in gears which have been subjected to heavy machining, in which case it is probably due to the release of strained surface conditions by heat treatment. As in other classes of work, the certainty of the results obtained by grinding is gradually winning a place for the ground gear. There are several types of gear-grinding machines on the market and several firms which make a speciality of grinding gears.

The generating process of grinding is used in some machines, while others depend upon the formation of a wheel to the profile of a tooth space. The generating machines use a wheel or wheels shaped to

a plane face, which is easily trued and restored. These plane wheels are applied so that they represent the straight side of a standard rack tooth and they are rolled in mesh with the wheel to be ground.

For the alternative process with the formed wheel, an enlarged template and a pantograph mechanism are used to guide the wheel-forming diamond. Very satisfactory results are obtained by each process, and each has its strong advocates. It is too soon to say whether either will ever entirely displace the other, although it seems likely that both will be developed and will continue to be used.

Measurements of Gear-Wheels

When gears are ground the quality of the working surfaces is smooth and regular enough to justify very refined methods of measurement. Such methods have been developed, and some of them are described below. For many purposes the test of noise is of prime consequence. If a gear-wheel will run at the designed speed under load without undue noise it is often passed as satisfactory. The test is really very exacting, because very small faults in pitch, form or surface quality are able to cause a considerable noise. If a gear fails to pass the silence test, then measurements will often indicate where the fault lies.

Measurements on gears may be classified into simply applied workshop measurements, which show as a rule the combined effect of several factors, and into more direct measurements which are applied to one element at a time.

A typical appliance of the first class has two vertical parallel shafts—one fixed at the end of a horizontal slide, the other carried on a movable member on the slide. On one shaft a standard or master gear of known accuracy is mounted to mesh with the gear under test on the other shaft. The two wheels are held in mesh by a spring which causes the slider to follow up any variations in eccentricity of the gear to be tested. Motion of the slide, as the wheels are turned, is read off a dial gauge or is recorded on a chart. Limits of eccentricity are assigned according to the class of wheel under test. The effects may be due to eccentricity of the pitch surface, to some distortion of the pitch surface or to a variation in pitch which changes the depth of engagement. Without some other test it is not possible to say which cause is accountable for the motion of the slide. But a wheel which shows little movement is generally satisfactory.

For direct tests on concentricity and on uniformity of pitch small steel cylinders are useful. When testing concentricity it is advisable to bear in mind that the tooth surfaces are not necessarily true with the outer diameter of the wheel. The blank is turned and bored, usually at one setting, and the bore is therefore likely to be true with the outside diameter, but the teeth are cut in a later operation,

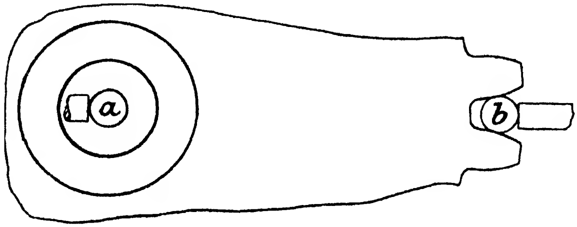


FIG. 182.

when the blank may not be set truly with its previously finished surfaces. If that should be the case the teeth will be cut at varying depths from the outside diameter and not true with the bore. There are several reasons why the blanks may not be set truly in the gear-cutting machine. Several parts are involved in mounting the blanks, such as the arbor on which they fit, the taper socket of the work spindle nose and the taper shank of the arbor. At any one of these

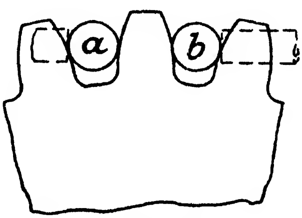


FIG. 183.

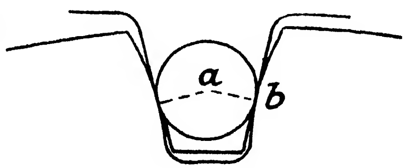


FIG. 184.

places some error may creep in, and it is never safe to assume that the teeth of a wheel have been cut truly with its bore or shaft. In order to check this point measurements should be made with a micrometer over a true cylinder, *a*, fitted in the bore and another cylinder, *b*, placed in contact with two adjacent tooth flanks as in Fig. 182. If this be done right round the wheel variations in the readings will show up any eccentricity of the tooth profiles.

A similar method is applicable to the measurement of pitch. Two equal cylinders, *a* and *b*, of appropriate diameter are placed in

adjacent tooth spaces and a micrometer measurement taken over their projecting ends, as in Fig. 183. Variations in pitch will be indicated by differences in the micrometer readings as the process is continued round the wheel.

Size of Cylinders for Gear-Tooth Measurements

Although it is not essential to select any particular diameter for the contact cylinder, the following size will be found to have certain advantages.

$$d=\frac{p}{2}\times\cos\,\theta.$$

where d=diameter of cylinder
p=circular pitch of wheel
θ=angle of pressure.

Referring to Fig. 184, it will be seen that when the centre, a, of a circle of this diameter is situated at the middle of a standard rack tooth on the pitch line, the circle is tangent to the faces of the tooth at the points, b, where that tooth would make contact with the teeth of a correctly formed gear-wheel. Therefore a cylinder of this size would make contact with the gear teeth at the same points, and the centre of the cylinder would lie on the pitch circle of the gear. The same cylinder will serve conveniently for the measurements of all the wheels of one pitch. Another advantage is that in teeth of correct thickness the distance from centre to centre of two cylinders is equal to the chordal pitch.

Enlarged Copies of Tooth Outlines

The measurements described above have the defect that they give information about very small parts of the tooth surface only. The contact between a cylinder and the tooth faces is merely a line. Therefore such measurements should be supplemented by information as to the tooth forms. A very interesting gear-measuring machine has been designed and used by G. A. Tomlinson at the National Physical Laboratory. In this machine the wheel to be examined is mounted on centres fitted with a sine bar attachment by which the wheel may be rotated through a known angle after the examination of each tooth. On the same bedplate which carries the centres there is mounted a pantograph device on a compound slide rest which enables it to be set at a distance from the line of centres to suit the size of wheel under examination, and provides also for its movement

along the axis for the examination of different parts of the same tooth. The pantograph is a very critical feature of the machine, since it is designed to trace with a delicate stylus a copy of the tooth outlines under test. The stylus is very delicately supported on parallel springs permitting motion parallel to the axis of the stylus, and is capable of drawing a line not exceeding 0·0002 inch wide on the smoked glass plate. As the ball point of the pantograph is moved carefully over the profile of a tooth, the stylus traces a copy on the plate. The copy is drawn actual size and is examined after enlargement by a horizontal projection apparatus. Since measurements of the order of accuracy of 0·0001 inch are necessary it is clear that the pantograph must work smoothly and without lost motion. This has been accomplished with such success that the pantograph method has been adopted after trial in preference to a method of locating several points on a profile by co-ordinates. One advantage of the complete outline is that irregularities are shown up which might escape notice if only a few points were found.

Comparison of the projected diagram with a correctly drawn involute will show any departure from true form. By an ingenious device it is possible to draw all the outlines for a wheel on a single plate. After drawing one outline, the wheel is indexed to bring the next tooth into position, but the index angle selected is slightly less than the angle subtended by one pitch. Thus the second tooth is brought into a position about 0·003 of an inch away from the first, and each tooth in turn is similarly displaced. The set of closely spaced diagrams shows up variations in tooth profile and variations of pitch very clearly even by visual inspection. If the teeth are equally spaced, the outlines on the plate will also be equally spaced, but any inequality of pitch will displace the figure of the irregular tooth on the plate. The displacement will be exaggerated to view by the closeness of the figures. If desired, actual pitch measurements to one ten-thousandth of an inch can be obtained from the projected view. Other elements of gear teeth which may be investigated with this machine are the symmetry of the teeth about a radial centre line and the alignment of the teeth axially. To determine the radial symmetry, a diagram is drawn for a given tooth, and the wheel is then turned end for end on centres. A second diagram is then drawn for the same tooth. If the tooth is symmetrical the two diagrams will coincide, but if it is not the fault will be doubled. To test the axial alignment of a tooth a series of figures are drawn

along the length of the tooth, by making use of the longitudinal slide of the rest which carries the pantograph. A clearer record is obtained if the wheel is indexed through a small known angle after each figure is drawn. In this way the confusion which would arise from closely superimposing one diagram on another is avoided.

Since the purpose of toothed gearing is to transmit motion evenly from one shaft to another, it is natural to apply a test which compares directly the speed of one shaft with another. In a machine for this

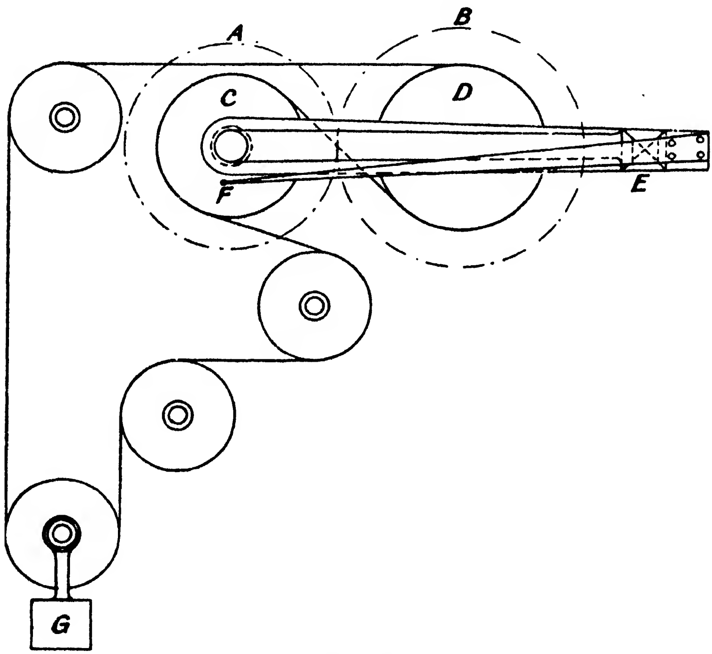


FIG. 185.

purpose there are two parallel shafts, and on one of the shafts there is a concentric sleeve. On the first shaft, Fig. 185, are keyed a master gear, B, of known accuracy and a plain cylinder, D. The gear, A, to be tested is mounted on the second shaft and is driven by the master gear. The concentric sleeve is driven by a steel band over two plain cylinders, C and D, whose diameters are in the same ratio as the pitch diameters of the master gear and the gear to be tested. If the gears are perfect there will be no relative motion between the sleeve and the second shaft. A recording device with a stylus, F, automatically makes an enlarged record of the relative

motion between the shaft and the sleeve. For perfect gears the record is either circular or spiral, the former if the ratio of the pitch diameters of the gears is exactly equal to the ratio of the diameters of the two cylinders, the latter if the ratios are not equal. Waves or undulations in the record indicate that the shaft, which is driven by the gears, is alternately overtaking and falling behind the steadily moving sleeve. The pitch of the waves is a guide to the cause. A long rise and fall lasting for one revolution indicates an eccentrically mounted wheel. Short waves occurring in a distance less than one pitch suggest faults in the form of tooth. Analysis of the diagram will usually lead to the discovery of the defect causing the variation in speed.

Gear-Tooth Caliper

Measurements of tooth thickness are often valuable, and the gear-tooth caliper is a convenient device for the purpose. It is made with caliper jaws on a graduated bar, very much like the ordinary vernier, but there is added to it a vernier gauge measuring depths at right angles to the primary vernier. By setting the depth gauge to the distance corresponding to the position of the pitch circle, the caliper can be used to measure the thickness of the tooth at the pitch line. The actual reading is, of course, the chordal thickness, and the depth gauge setting must be obtained as follows:

$$\text{depth setting} = \text{addendum} + r\left(1 - \cos\frac{360}{4n}\right)$$

where r = pitch radius
n = number of teeth.

The description above refers to the instrument made by the Brown and Sharpe Co. A somewhat similar instrument, but differing in the use of glass scales read with the aid of a lens, is made by Zeiss.

These calipers may be applied to test the tooth form by taking a series of thickness measurements at various distances from the top of the tooth. In using the calipers it must be remembered that the outside of the gear may not be concentric with the tooth faces so that allowance may be made in setting the depth gauge.

An alternative method of gauging the involute of the tooth faces depends upon the fact that a constant distance separates two involutes of the same base circle. Consequently the two jaws of a gauge placed in contact with similar faces of two adjacent teeth and rolled

over them should maintain a constant distance if the curves are correct. In the instrument one jaw is adjustable to suit the pitch of the wheel under test, and one is held in contact by spring pressure. Any motion of the latter is shown on an enlarged scale by an indicator.

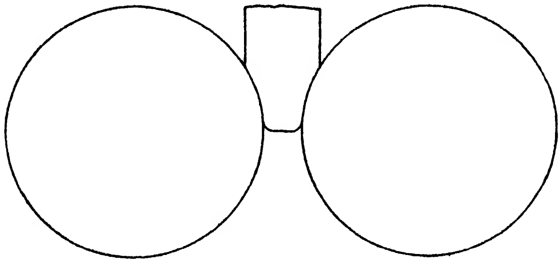


FIG. 186.

Fig. 186 shows a method of using discs to verify the curves of a template for wheels of more than thirty teeth.

It is not suggested that all wheels should be tested by the methods described above. Complete examination is not often required except for comparison of the results obtainable by different processes of gear cutting and finishing. Once a process has been selected as suitable for a particular purpose, it is merely necessary to make such comparatively simple inspection as will ensure conformity to the standard set. Complete measurement is rarely needed for this.

CHAPTER XIII

LAPPING AND GRINDING

BOTH of these are abrasive processes, and the distinction between them cannot be expressed in a few words. It is to be understood that precision grinding is here referred to, not that grinding which is done freehand. Freehand grinding is used either for the rough removal of metal or for finishing work in which precision of form is of little consequence.

Between precision grinding and lapping there are points of similarity. Both employ abrasive particles to remove metal. Both are essentially finishing processes, and there is a field in which both may be used indifferently. They differ in the speed of the abrasive surface, but the principal difference is in the method of controlling the cut, that is, in the means of guiding the cutting points in relation to the work.

In precision grinding the wheel is used as a substitute for the ordinary cutting tool used in machining operations, because either the work is too hard to be cut by ordinary tools, or more exact results are obtainable by grinding even on soft work. The work is caused to move in paths determined by the slides or surfaces of the grinding machine. The wheel is also guided by its own independent slides; therefore the finished shape of the work depends principally upon the slide-controlled motions of the work and the grinding wheel. It is rarely a copy of the shape of the grinding wheel, although there may be some resemblance in form grinding.

In lapping, the finished form of the work depends upon the shape of the lap and is essentially a copy of the lap in reverse. The lap is usually a piece of some metal soft enough to permit abrasive particles to be embedded in it. The metal blank for the lap is first turned, planed, or in some other way machined to the desired shape. It is then dressed with the abrasive so that some part of the grit is retained in the surface of the blank. The particles retained project slightly from the lap, and when the work and the lap are rubbed together small chips are cut from the work. The depth of cut is limited by the surrounding metal and is very small. The effect produced is

very like extremely rapid wear of the work, so that the more prominent parts above the general level are rubbed down. Nowadays for production lapping, bonded laps of very fine abrasive are often used.

Considering a simple case, such as, for example, an approximately flat surface to be lapped on a very nearly flat lap, it is clear that only the raised portions of the work will be reached by the cutting points and that they will be slowly reduced as the work and the lap are rubbed together. But the depressed parts will not be touched by the abrasive provided the area of the lap is great enough to span the distance between the high places on the work. The general effect of careful lapping is to bring the surface of the work to a common level or contour similar to that of the lap. It is quite possible for the finished work to be more truly formed than the lap, since it need not follow all the contours of the lap.

The best results are obtained from lapping when the lap is moved in all directions over the surface of the work. In this way all parts of the lap are used equally so that localised wear and change of shape are prevented. This condition of motion in all directions can only be satisfied if the radius of curvature is either constant over all the surface or is constant in each of two directions. It implies that all parts of the lap will fit all parts of the work. The plane is one example, since it is obvious that two plane surfaces will fit together in all parts. The sphere is another example, or rather, the plane is a particular case of the sphere. Two spherical surfaces of the same radius, one convex and one concave, will fit together in any positions in relation to one another. Thus a freedom of motion is permitted which enables wear to be distributed with perfect uniformity over the whole surface. Cylindrical surfaces do not allow quite so much freedom of motion, but they still have sufficient freedom to permit wear to be distributed evenly over the whole surface.

It is interesting to think of this matter of lapping in the terms of Chapter VI. Considering a part of a hollow sphere resting upon a solid sphere of equal radius, it is clear that the partial sphere may be rotated in any direction. That is to say, it has complete rotational freedom. If the partial sphere be of relatively small dimensions it will appear to have two degrees of translational freedom, that is, it may be moved to the right or left, or it may be moved backwards or forwards. But further thought will show that these two possible motions are merely aspects of two of the rotational motions. This will be clear if an almost complete enclosing sphere be thought of.

Considering a sphere of infinite radius, that is, a plane surface, it is obviously possible to move a small plate in any direction in the plane, but not to lift it from the plane without breaking contact. The plate may also rotate about a vertical axis. Therefore in this particular case there are three degrees of freedom. The two translations are of course rotational movements about two infinitely distant axes.

Take next the case of two cylinders fitting together. There may be relative rotation about the common axis. There may also be relative translation in the direction of the common axis. Thus there are two degrees of freedom only. But these two are sufficient to permit any part of one member to make contact with any part of the other member, because these freedoms are quite independent of each other. These considerations are supported by the observed fact that by careful use it is possible to preserve the shape of spherical and cylindrical laps without frequent retrueing. Cylindrical laps were in use for rectifying hardened steel machine parts many years before the introduction of precision grinding machines. They were for a long time the only available means of producing true surfaces on hardened steel. When properly designed and used, both the lap and the work are brought more and more nearly to the cylindrical form. They are now to some extent superseded by the grinding machine, but they are still used to finish some of the highest grade of work.

Laps for plane surfaces can be used in such a way as to cause uniform wear, but, as already pointed out, there is no limit to the number of ways in which the lap and the work may be rubbed over each other.

In contrast to the cases quoted above, in which the lap automatically retains its shape, is the case of conical lapping. This is never really satisfactory although it will give moderately good surfaces provided there is little correction to be made in the lapping process. The relative motion is restricted to rotation about the common axis of the lap and the work, and there is a tendency to wear circumferential grooves and ridges. This cannot be corrected by moving the lap endwise, because there is only one position in which the diameters coincide. In cylindrical lapping the formation of grooves is prevented by sliding the lap along the work. The scratches are diagonal and cross each other.

Screw threads for gauges are often lapped. Here again the relative

motion is restricted and the laps are not self-correcting. That is to say, a tendency to wear the lap low in one place cannot be checked by moving the lap in a different path over the work. At first sight it might appear that a thread lap would have two degrees of freedom over the work. It rotates and it moves longitudinally. But these two motions are combined in a definite ratio so that the motion is confined to a single path. That is, there is only a single corkscrew type of motion possible, and any particular point on a thread lap moves over the work in one definite track. It may move to a greater or less extent, but its path is fixed. There is a tendency therefore to form grooves as there is in conical lapping, but it is less pronounced because the length of rubbing surface is relatively great and there may be overrunning at each end. In spite of this, thread laps must be reshaped after a very moderate amount of use.

Typical Laps

Fig. 187 shows two laps, A and B, for external cylindrical surfaces. They all consist of a holder, by means of which the lap can be closed in to compensate for wear of the lap and for the diminishing size of the

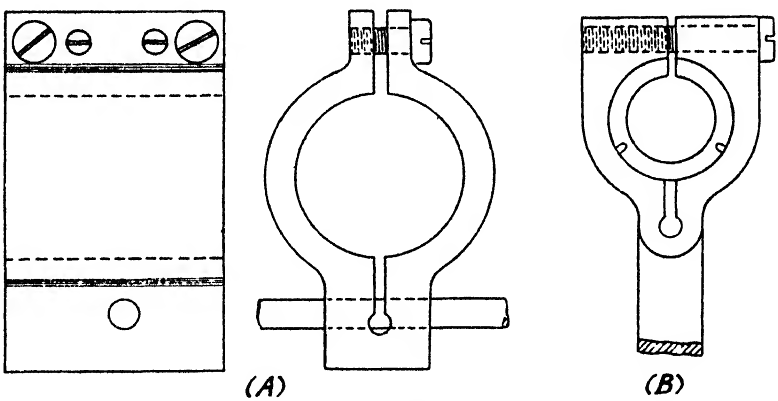


FIG. 187.

work. Contact between the lap and the work is always over relatively large surfaces, even though it does not include the whole surface. It is always sufficient to prevent any tendency of the lap to follow up the depressed parts of the work. The lap itself is of mild steel or porous cast iron in the form of a partially split bush, as in Fig. 187.

Some people prefer cast iron because it is said to have numerous

cavities in which the abrasive lodges. Others prefer mild steel because they consider the grit is embedded in the surface and therefore gives more precise results than the more or less loose grit in a

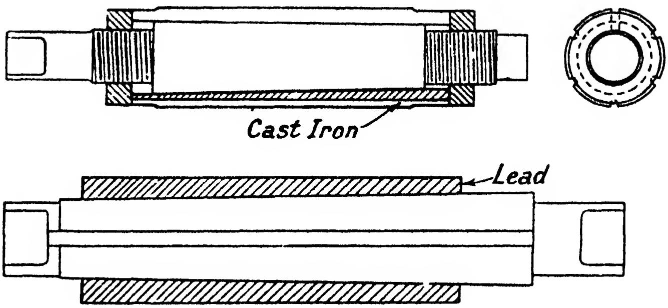


FIG. 188.

cast-iron lap. The choice appears to be a matter of opinion, since both materials are satisfactory when properly used.

For hollow cylinders, laps of the kind shown in Fig. 188 are used. These are made so that, as they wear smaller and the work is gradually enlarged, they may be expanded by means of the tapered centre.

Screw-Thread Lapping

Until the method of grinding hardened screw threads by a formed wheel was developed it was necessary to use laps to rectify the distortion caused by hardening. As the special grinding machines and the attachments used for grinding screw threads are not always at hand, the lap is still much used. It can be made and applied with such resources as are to be found in most machine shops. The most serious fault and the one most difficult to correct is incorrect pitch. This may arise from errors in the lathe on which the screw was cut. It is more likely to arise from changes which occur when the screw is hardened. In either case the error in pitch must be corrected. There is some risk that in doing this the form of the thread may be injured and that the diameter of the thread may be reduced below the permitted limit. The latter is unavoidable if the pitch error turns out to be greater than was allowed for in turning the screw. The allowance for pitch correction is not easy to estimate. Slight variations in the steel, even from a known bar, and in heat treatment are quite enough to make the estimates wrong. When this happens there is no remedy except to start again with a bigger allowance. There is an objection to making the allowance greater than is absolutely

required, because lapping is a slow and expensive process, and is difficult to localise if much is to be removed. If excessive allowances be made the prominent parts of the thread are apt to be removed more quickly than the others. Thus the crest of the thread may be unduly removed and the thread angle made more obtuse.

The use of special laps, each made to act upon one part of the

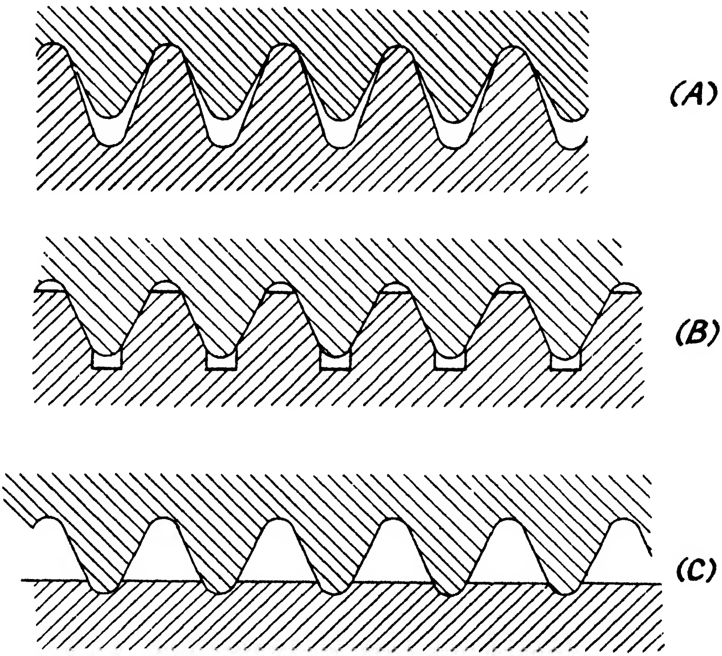


Fig. 189.

thread outline is necessary if the faults in the hardened thread are serious. Fig. 189 shows a set of laps for a Whitworth form thread. The lap is the lower member in each part of the diagram, and the screw to be corrected is shown in the upper position. Fig. 189 (A) shows a thin thread form, of which the thread angle is several degrees less than 55°. The radius at the crest is of the standard value, but the flanks will clear the flanks of a truly formed thread. This lap is used to deepen the root of the thread in the gauge without affecting the other parts. The root is the most troublesome part of the thread to reach with a lap, and it is good practice to cut the thread slightly deep in order to avoid much lapping at this point. Fig. 189 (B) is an effective diameter lap. It is truncated at the crest

and cut deep at the root. These two portions would otherwise act upon the root and crest respectively of the gauge. After correcting the root and effective diameter, that is, the flanks of the gauge, it is not unusual to find that the crest is down to size, since this is the most prominent part of the gauge and is liable to be reduced by the laps used on other parts, especially if much loose abrasive is used. If the crest should still be high it may be reduced by the lap shown in Fig. 189 (C).

Correction of Pitch Errors

The action of the lap in correcting a pitch error is illustrated in Fig. 190. It is assumed that the lap is of correct pitch or nearly so. This is the less difficult to ensure, because the lap is used in the soft condition as cut, that is, without risk of change owing to heat treat-

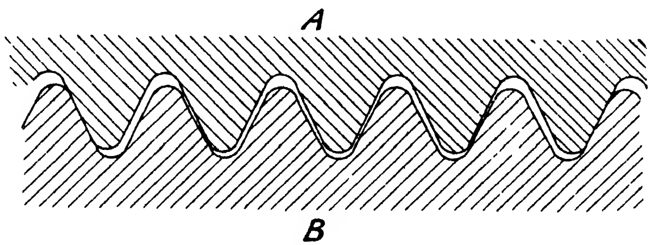


Fig. 190.

ment. The contact between the gauge B and the lap A is localised at the inner faces of the end threads. These parts will be reduced as the lapping proceeds, tending to make the thread thin at each end. As this happens the lap will be closed in and the central threads of the gauge will be reduced evenly. Finally, when the lap makes contact on the outer sides of the end threads, the pitch should be correct. By this time the effective diameter will be smaller, but it may still be over size, in which case further lapping with the effective diameter lap will reduce the diameter, while leaving the pitch unchanged. The pitch is only altered by lapping when it differs from the pitch of the lap.

When using laps for local action on different parts of the thread as described, the projection lantern is an extremely valuable aid. It enables the effect of the laps to be observed and their use to be stopped at the right time to preserve the required cross-section of thread. Diameters should be checked from time to time by direct micrometer measurement. This is more certain than measurements obtained by

the projection apparatus, on account of the slight lack of definition consequent on the transverse curvature of the gauge.

The usual way of applying the abrasive to a lap is to make it into a thin paste with oil and to put a few spots on the gauge. This is pressed into the surface of the lap as it is screwed on and forms a satisfactory cutting surface. Too much abrasive should not be applied as it will form a rolling mass of grit between the gauge and the lap. It will not cut properly, and the true form of the lap will not be reproduced on the gauge. Once the lap has been treated as described fresh abrasive should only be applied sparingly and at long intervals, but thin oil or paraffin may be used to assist the cutting action by clearing away waste material. These remarks about the preparation of a lapping surface are applicable to any laps, whether for screw threads or any other purpose. Lapping is not a rapid process, and it is natural to try to hasten it by the generous application of abrasive. Experience will show that loose grit does not accelerate the process and that it tends to blur the edges of the work instead of producing a clear cut form.

Lapping End Blocks or Gauges

The lapping of end gauges by the patented process as developed at the National Physical Laboratory is an interesting example of plane lapping. The gauges are prepared and lapped in batches of eight, all of similar size. After grinding they are assembled on a magnetic chuck, Fig. 191, A, B, etc. At this stage they will be within a small tolerance above the nominal size. They are rubbed on a plane lap until their surfaces are good enough to enable them to be wrung to the plane surface of a carefully finished block. After demagnetisation, and while wrung to this block, they are lapped until all the free end surfaces are in one plane. They are not then necessarily all of the same length, so certain of the gauge blocks A, D, E and H are measured, and if they are found to be unequal

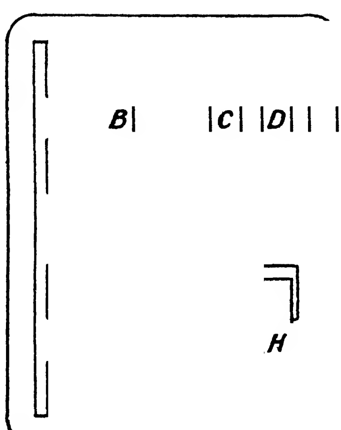


Fig. 191.

in length they are interchanged diagonally, as shown in Fig. 192. In this way the average height of the blocks at the corners is equalised. It is said that when this has been done once or, at most, twice, and the blocks lapped flat each time, they will not be more than a few

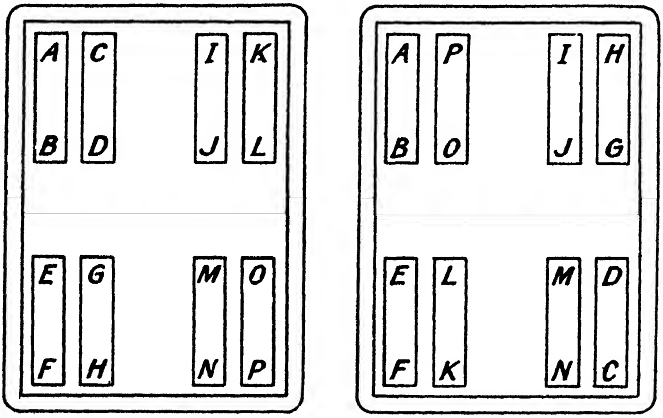


FIG. 192.

millionths of an inch different in length. The separation of the gauge blocks over a relatively large area and the averaging of the heights are important factors in the success of the method. The separation checks the tendency to rock and so to produce curved faces which is troublesome when lapping a small area. Interchange of the gauges ensures that parallel end faces are produced over a large area, so that there is no doubt of the truth of individual gauges.

Machine Lapping

Lapping in batches is applied to the finishing of cylindrical and spherical parts. This is different from the methods described so far, in that there is line rather than surface contact between the lap and the work. Take, for instance, the lapping of gudgeon pins. These are ground nearly to size; within say, 0·006 inch. The laps are circular discs either of bonded abrasive or of cast iron dressed with abrasive. Bonded abrasive wheels for use in lapping machines are made normally of grain sizes from 150 to 400, but they are obtainable as fine as 600 grain. One of the discs is mounted rigidly on a rotating vertical shaft, while the other is mounted above it so that it can float to suit the thickness of the work. A batch of gudgeon

pins is distributed between the plates in such a way that as the plates rotate the pins partly roll and partly slide between them. They are moved about so that the whole of the plate surface is used. Clearly any pins which are above size, either wholly or on any particular diameter, will be reduced more rapidly than the rest because they will take most of the weight of the upper lap which rests on them.

The central part of the two plates is recessed so that the working surface is an annulus. If the piston pins were placed radially on the annulus they would roll except for the small amount of slip on account of the variation in speed of the disc with its diameter. If the pins were placed tangentially on the lapping plate the relative motion between pins and plate would be almost entirely sliding.

By setting the pins tangentially to a small circle concentric with the plates a combination of rolling and sliding is obtained. There is the necessary rubbing for abrasion and sufficient rotation to present the whole of the cylindrical surfaces of the pins to the laps, bit by bit. The pins are held in slots in a disc between the two laps and the disc is given a regular circular motion eccentric to the laps, which brings all parts of the lap surfaces into action once per cycle. In this way the rate of wear is kept fairly constant over the whole surface. In case local wear does occur, the two plates can be lapped together until they become flat again. In the case of bonded laps, trueing is done by diamonds which are fed across in a straight path, much as in trueing grinding wheels.

A similar arrangement of opposing discs is used to lap the faces of end blocks and other parts which must have two faces accurately parallel. There is, of course, no rolling motion in this case. The blocks are placed in loosely fitting holes in a disc between the.lapping plates and are moved about by a sweeping circular motion of the disc.

Work which is to be lapped is usually ground to within about one half-thousandth of size in preparation. By the lapping operation it is easy to work to one ten-thousandth of an inch of size commercially. It is, ot course, possible to work much closer than that by the method. In gauge work the tolerance may be within one hundred-thousandth of an inch.

Diamond Lapping

The method known as diamond lapping as applied to the finishing of small diameter holes in hardened steel is not strictly lapping,

although the diamond laps are prepared in much the same way as other laps, namely, by pressing the abrasive particles into a metal surface. But the diamond lap is used as an internal grinding wheel. It makes contact with the work only along a line and not over its whole surface. The particles of diamond are exceedingly sharp and durable. They cut keenly and with very little pressure. Hence it is possible to use a diamond lap of very small diameter, without risk of bending it, providing the cut is not hurried.

Diamond laps of this kind are made by rolling the steel blank A, Fig. 193, between two hardened steel plates upon which a little

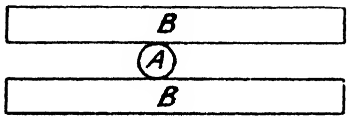


FIG. 193.

diamond dust has been placed. The dust is pressed into the surface of the lap and is held strongly enough to resist removal by proper use for a long time. Considerable patience is needed to obtain a sufficiently fine grade of diamond dust for use in laps. The usual method is to mix the diamond dust with oil and to separate out that dust which requires a certain length of time to settle. The finest dust may require several days to settle out of sperm oil. The dust is graded according to time of settling from one hour onwards.

Quality of Lapped Surfaces

There is a general impression that lapped surfaces are much more durable as working parts than ground surfaces are. Microscopic examination of the two kinds of finish supports the opinion. At about two hundred to two hundred and fifty magnifications a very finely ground surface of hardened steel appears to consist of narrow grooves separated by even narrower ridges or lands, the average width of a groove being about 0·0002 inch. The area of actual metal at the full diameter is less than fifty per cent of the full nominal surface of the ground part. The grooves run in the direction of motion of the surface of the grinding wheel, that is, in the case of a cylinder round the surface at right angles to the axis. In lapped work magnified in the same way grooves or scratches are still visible, but it is noticeable even in rough lapping that the scratches do not

occupy nearly so much of the total area. The effective surface existing at the full diameter is a much greater proportion of the whole. Another difference which probably has an influence on the durability, is that the scratches on a well-lapped surface lie in many directions over each other. The general effect produced by lapping is to remove the crests of a ground surface down to the bases of the intervening hollows. This involves the removal of 0·0003 to 0·0005 inch. Since it is not possible to prevent the intrusion of an occasional particle of larger grit, there are scratches on the finished surface which show up the more prominently in the general smoothness. The irregularity of these scratches causes them to stand out unduly in comparison with the uniformly grooved surface produced by grinding, so that at first sight the lapped surface may compare unfavourably with a ground surface.

Although hand lapping is capable of producing very good work, considerations of output encourage the use of mechanical lapping. This will give at least as high quality as hand lapping and the time and attention required are much reduced.

There are certain factors which are definitely in favour of machine lapping apart from the higher rate of production. In flat surface lapping, for instance, the machines are designed to use two laps, one on each face of the work, and the work is moved about between these in a circular path by a spider. The use of two laps checks the tendency to rock, which is always present when a single lap is used. The mechanically operated spider avoids contact of the hands with the work, and gives a regularity of motion which is in itself an advantage. Temperature changes are of great importance in their effect on precision lapping, hence the importance of avoiding hand contact. The effect of chilling one side of a piece of steel and warming the opposite side is to cause the cool side to become concave. If the cool side be lapped on a flat surface in this condition it will be flat as long as the temperature distribution remains constant, but as soon afterwards as the temperature is equalised throughout the piece the lapped surface will become convex.

A difficulty in hand lapping is the tendency to rock when the surfaces are very nearly alike. This arises from the oil used in lapping or from an air film in dry lapping. When the work is rubbed over the lap the fluid, whether air or oil which lies between the two surfaces, cannot be entirely squeezed out and prevents contact between them except near the edges as the work rocks on the film. This

difficulty may be overcome by cutting narrow grooves across the lap, dividing it into quarter or three-eighth inch squares. The grooves afford a ready outlet for the air or oil, but they should have sharp edges. Rounded edges will feed oil between the laps and keep them separate, according to the principle which underlies the Michel bearing.

The tendency of large flat surfaces to maintain a film of air or other fluid between them is responsible for the difficulty of lapping three plates together in various combinations to produce three planes, according to the principle followed in scraping surface plates. One plate of each pair is almost sure to be convex because it is nearly impossible to prevent some rocking motion. It is, in practice, found more convenient to prepare several pairs of plates at once and to select the flat ones rather than to attempt to make all the plates flat.

Speed of Laps

The speeds used in lapping are somewhat difficult to estimate. They are undoubtedly much lower than grinding speeds, being of the order of a few hundred feet per minute against several thousands for grinding. In hand lapping for flat surfaces the rubbing speed is between 50 and 200 feet per minute. For cylindrical lapping with a hand controlled lap the peripheral speed of the work will be rather less and the lap should be so moved to and fro longitudinally that the scratches on the surface will run diagonally at about 50° or 60° to the axis.

Machine laps for flat surfaces are used at similar speeds to hand laps. The motion is sometimes derived wholly from the work spider between two stationary laps. Sometimes the laps are rotated in opposite directions at slightly different speeds, and the eccentric movement of the spider and the work is derived from the creep of the work. Whether the speed of machine laps has been derived from those found satisfactory in hand lapping or whether higher speeds have been systematically tried and found useless is not known. Speeds such as would cause an appreciable rise in temperature would clearly be of little use for accurate work.

Centreless Grinding. Lobed Cross-Sections

A process which has some points of resemblance to lapping is that known as centreless grinding. As in lapping, the work is supported

and guided by the finished surface and the same tendency to become lobed or out-of-round, exists in both processes. The work is held up to the grinding wheel A by the slower running regulating wheel B and the work rest C in Fig. 194. This method of support permits the work to float to and fro between the wheels if the contour is irregular,

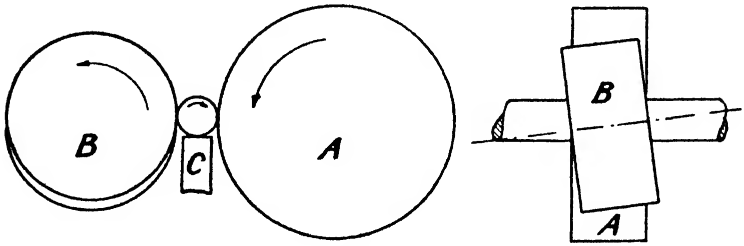


FIG. 194.

but there is most rapid cutting at the ends of any diameters which are above the general size. The work is therefore reduced gradually to a constant diameter, but the cross-section is not necessarily circular. The existence of constant diameter, or very nearly constant diameter, figures other than circular has been brought into prominence by the great extension of the use of centreless grinding. These are figures bounded by a line of varying curvature, so that diametral measurements in all directions are equal. They will not pass through a ring gauge of their own nominal diameter because the ring gauge measures the highest points and misses the lower parts between (see Fig. 195).

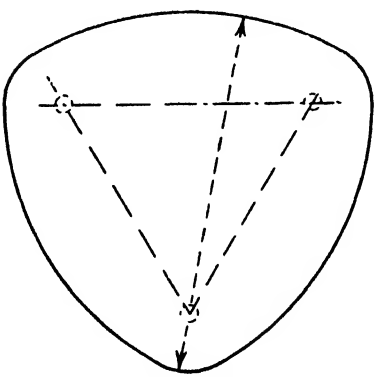


FIG. 195.

The figures appear to arise from some irregularity in the rolling, rather as if they rolled alternately on the feed wheel and on the grinding wheel. Very rapid cutting is supposed to be liable to cause the action, although it is not fully understood, nor is it always easy to check when once it is established It occurs in cylinder lapping by means of flat laps of the machine type, and special measures must be taken to remove it before finish lapping the last ten-thousandth of an inch from plug gauge or other

very precise work. The out-of-roundness which arises during the rough lapping process is small, being only a few ten-thousandths of an inch, but it is too much to permit in a gauge. It is easily removed by a brief hand lapping with a ring lap, after which the gauge may be finished to size without any appreciable recurrence of the out-of-round form.

For many purposes the lobed form is not objectionable. Its existence is said to have been realised when plug gauges having passed a snap gauge failed to pass a ring gauge of the same size. Careful investigation showed that the gauges were not circular. A usual test now applied is to gauge suspected pieces on a vee block below a comparator, thus using three contacts.

It is very easy to exaggerate the importance of the tendency to produce lobed rather than circular cross-sections when work is lapped

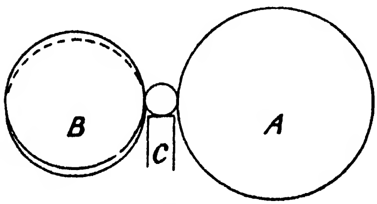


FIG. 196a.

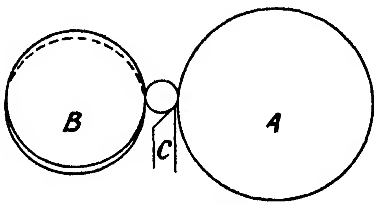


FIG. 196b.

between plates or ground between wheels as in the centreless grinding process. Even when it occurs, the out-of-roundness is not often perceptible without very precise measurements, being usually of the order of hundred-thousandths of an inch. An alteration in the shape of the work rest is found to reduce the tendency in centreless grinding. If the lobing is troublesome when the ordinary pattern of rest, Fig. 196a, is used, a change to the rest shown in Fig. 196b will eliminate or reduce it. As will be seen, the rest B holds the work more definitely up to the controlling wheel. In especially troublesome cases it may be necessary to experiment with variations of the angle of the rest.

There are certain advantages of the centreless method of grinding in addition to the saving in time in not using centres in the work and in the speed of feeding the work to the machine. The control wheel provides a very complete support for the work, holding it up for the full length of cut. Take, for example, the case of long cylindrical work with a continuous feed through the machine. The grinding wheel is trued parallel to the axis, that is, parallel to the direction of

feed. The inclined feed wheel is trued by a diamond which is moved in a straight line at such an inclination to the axis of the feed wheel that the wheel face is finished straight and parallel to the grinding wheel at the line of contact, *cd*, with the work. The control wheel is of course slightly hollow in an axial section. This will be clear on reference to *ab*, Fig. 197. When the work is passed between the wheels the space between the wheels becomes slightly tapered by the wear of the grinding wheel on the entering side. The taper will ultimately become equal to the difference between the original and the finished diameters. In this condition it should remain for a considerable time, wear taking place uniformly and the size of the work being maintained by feeding the control wheel inwards from time to time. There is a trueing diamond permanently mounted on a slide for each wheel, usually near the top of the wheel out of the way, so that the wheels may be trued without loss of time whenever required. Some machines have a quickly operated speed change for the control wheel to bring it to a more suitable speed for trueing.

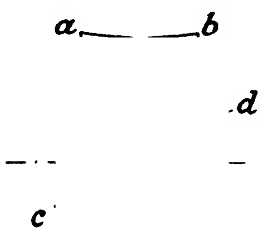


Fig. 197.

This type of machine has been developed to deal with shouldered and tapered work. The wheels are set with their axes parallel, since there is no longitudinal feed, and the work is dropped into place and brought to size by an in-fed of the control wheel. Both are formed to special shapes by the use of a former plate to guide the diamond. Wheels up to 12 or 15 inches wide are used, and proportionately long work can be done.

Screw-Thread Grinding

Another very interesting application of form grinding is applied to the finish grinding of hardened screw threads. In principle the process is simple, being akin to thread milling, but much tedious experimenting has been necessary to overcome the practical difficulties. One phase of the problem, the provision of the right kind of wheel, has depended on the wheel maker for its solution, and it has been answered so successfully that wheels capable of grinding even micrometer screws of one-fortieth of an inch pitch from the solid are now available. The difficulty of making a wheel which will maintain a formed vee edge within a width of one-fortieth of an

inch can easily be imagined. A simple pair of straight forming plates at the desired angle serve to guide the trueing diamond, but the wheel must be of a quality which will enable it to cut freely without measurable wear for a reasonable length of time so that at least one thread can be finished without change of size or shape after trueing the wheel. The root form may depend upon the natural crumbling of the extreme corner of the wheel, and therefore upon the right choice of bond and grain. In machines now made for thread grinding, the diamond is guided by a former to true the edge of the wheel to the full form of one or more threads. Micrometer screws, which are now more usually hardened than they were some years ago, need not be specially formed to fit at crest and root. In fact, it is better that they should clear at these points and should make good contact on the flanks. Therefore the thread in both screw and nut should be cut deep in the root, *a*, and may be left flat at the crests, *b*, as in Fig. 198. Such fine-pitched threads are often ground from the solid, hardened blank.

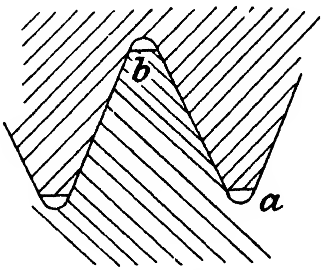


FIG. 198.

Finishing Machine Tool Slides by Grinding

Long after the grinding machine had justified its application to the finishing of shafts and of plane work, attempts were made to use it for finishing machine tool slides. Hitherto these had been scraped to form the necessary plane surfaces. There was, after many years of scraping, a strong feeling in many quarters that no other method could produce equal results, either in truth or in quality of surface. But after trials, which stimulated the development of suitably heavy surface grinding machines, it has been found possible to finish the slides of machines in this way. Contrary to expectation, they are said to be easier to lubricate and lighter running. In a scraped surface it is well known that the actual contact is on the higher spots and that these are separated by hollows. The hollows were supposed to perform a valuable function by retaining oil between the surfaces. It is now suggested that the increased area of contact obtained by grinding reduces the intensity of pressure and thereby helps to retain the oil film and to reduce the rate of wear.

There is one point in favour of grinding the slides of machines which should not be overlooked. The use of the grinding wheel instead of the scraper will permit harder varieties of cast iron to be used. This is of increasing value on account of the use of rapid cutting alloys, and the great difficulty of keeping machine ways clear of cuttings. Under these conditions the ways wear very rapidly unless they are made of special material or are carefully guarded with fitted covers.

CHAPTER XIV

SURFACE FINISH

In the previous chapter, on p. 241, lapped surfaces were compared with ground surfaces, the comparison being based on visual examination of the two surfaces and on their behaviour in service. The value of lapped surfaces for gauges has long been known. More recently it has been realised that there are other cases where components finished to the same tolerances by different processes may differ very greatly in their efficiency or endurance. A few such cases are mentioned below by way of illustration. Honing the bore of a ground cylinder for an internal combustion engine will increase its life as compared with a cylinder which has been ground only. Heavily loaded journals will work at a lower temperature and will last longer in proportion to the smoothness of their finish. The barrels and plungers of the injection pumps of high compression oil engines must not only be correct to size, but they must also have exceedingly smooth working surfaces to maintain oil tightness against the high working pressure of two thousand pounds or more per square inch. For all these purposes, and for others where exacting conditions have to be met, it has been observed that the minute texture of the surface is of hardly less importance than the general truth of form.

Distinction between Geometrical Accuracy and Fine Finish

Almost any machined surface, for example a ground cylindrical bar, may be shown by careful measurement to vary slightly in diameter from point to point along its length and also in different directions in the same cross-sectional plane. Such variations may be observed by means of the ordinary micrometer having contact faces about a quarter of an inch in diameter. They arise from errors in the machine slides and from deflections in the machine or work under the forces of cutting. But the micrometer would not distinguish between a bar ground with a wheel of 30 grain size and another bar ground with a wheel of 80 grain, although there might be a very great difference between the

two surfaces. The micrometer indicates the dimensions of the high parts of the surfaces and takes no account of the depth of any grooves or pits which lie within the area spanned by its faces. Provided the spacing of the high places does not exceed that area no difference in dimensions will be shown although the finish may be quite unlike in the pieces examined.

Classification of Surface Imperfections

The faults in a machined surface may be divided roughly into three classes according to their wave-length, since the defects which generally occur are of a recurrent character and the resultant surface is the sum of a number of undulations of various periods and amplitudes. Analysis of typical surfaces will usually show the presence of long, medium and short waves. Although the boundaries of the groups are not yet exactly defined, certain limits appear to be commonly accepted. Waves over 0·200 inches are regarded as long. These are likely to arise from defects in the machine such as untrue or unduly light slides or from excessive clearance in bearings. Such defects should be eliminated before fine finishing is attempted on a machine. Medium waves are frequently referred to as waviness of surface and include waves between 0·01 and 0·100-inch pitch such as may be caused by the traverse of a cutting tool or grinding wheel. Short waves are of less than 0·010 inch and, among other causes, may arise from the grains of a grinding wheel or the traverse of a tool used for fine boring.

Methods of Measuring Surface Finish

Some of the methods described below are for comparison or estimation rather than exact measurement. The well-known difference in the drag or bite of a coin drawn cornerwise over two surfaces differing in finish, e.g. ground and honed, is an example of the comparative type. With practice it is possible to grade a series of surfaces fairly well by this method.

Visual comparison of surfaces is apt to be misleading except where the same process of finishing is employed in all the cases compared. The same limitation must be applied to microscopic examination of surfaces. Sight, either unaided, or with the microscope, is impressed by brightness and by the pitch of irregularities and is little affected by the more important factor, depth.

Taper Sections

This is the name given to the device of cutting away part of the surface to be examined to a plane intersecting the surface at a very small angle. The depth of any scratches or impressions intersected by the oblique plane is greatly exaggerated and becomes readily measurable with the aid of a microscope. The pitch of the depressions being usually much greater than their depth does not require the additional enlargement derived from oblique sectioning.

Interference Method

Vertical mono-chromatic illumination is used in conjunction with the microscope to form interference fringes between the surface and a glass plane slightly inclined to it and resting upon it. Scratches are shown up as waves or zig-zags in the fringes and their depth may be estimated from the spacing of the fringes if the light has a known wave-length.

The Profile Microscope

In this method the profile of the surface is shown by a thin flat sheet of light, which is directed through a narrow slit to meet the surface at an angle of 45°. The outline revealed in this way is seen by means of a microscope placed with its axis at right-angles to the direction of the light. The scale of depth is enlarged by the oblique intersection in the ratio 1·4 to 1. This is additional to the subsequent magnification, which affects both depth and pitch.

Stylus Instruments

Some of the foregoing methods are not capable of giving such complete information about the nature of a surface as is desirable for evaluating and controlling the results obtained from production processes. Others involve the destruction of the component or are not suitable for use in a workshop. In consequence the tracer or stylus instrument has been developed. One example of this type of instrument, designed by Dr. G. A. Tomlinson, has been used for the investigation of medium length waves with a first amplification of 40 to 1 by mechanical means and a further amplification optically by projection. The motion of the stylus relatively to the flat soleplate, 1¼ inches square, which rests upon the work is transmitted to a scribing needle whereby a record is traced on a smoked glass plate. A motion perpendicular to that of the scriber is given to the glass plate by a reducing

gear so that two inches travel of the soleplate over the work is equivalent to one-quarter of an inch travel of the record plate. The graph so drawn is examined with the aid of an optical projector giving an enlargement of fifty times, when the resultant vertical scale becomes 2,000 to 1 and the horizontal scale 6·25 to 1. A stylus or probe terminating in a one-sixteenth of an inch diameter steel ball is used with this apparatus in order to pass over the minute irregularities. It appears that an investigation with this kind of surface recorder should precede tests on the finer texture, that is upon the short wave irregularities, since it has been found that machined surfaces may have undulations up to half an inch in length, possibly derived from coarse roughing feeds in earlier processes. These undulations would be completely ignored by instruments designed to reveal the short wave texture, yet there is no reason to suppose that macro-roughness, as it is sometimes named, is of less importance than micro-roughness. As an example of the two kinds of roughness, a pin ground on a centreless grinder may be taken. Such a pin may have a three-lobed form in cross-section, differing from true circularity by nearly one ten-thousandth of an inch, but this would not appear in an examination with the kind of instrument about to be described.

Stylus Instruments. Micro-roughness

The success of these instruments depends upon two factors. One factor is the use of a very finely-pointed stylus having a nose radius of one ten-thousandth of an inch or less. Another factor is a means of amplification of the motion of the stylus up to forty thousand times the actual value without requiring more than a very small operating force. As little as six milligrammes have been used successfully, but about one hundred milligrammes are usually employed. This low limit to the operating force is necessary in order to avoid scratching the surface with the fine point of the stylus. Amplification is effected by means of an electrical pick-up in conjunction with the thermionic valve. The motion of the stylus is measured relatively to a skid whose face is curved to a radius of about one inch. When such a skid is drawn over a surface it follows the major undulations which thus become the reference surface and the stylus indicates the minor variations from the general outline. Referring to the example of the lobed pin mentioned above, it will be clear that a stylus used with a skid located from the general surface of the pin would give the same record for the lobed pin as for a truly cylindrical pin. The only differences which might be

observed would arise from variations in the fine or short wave texture of the two pins. For some purposes it may be desirable to obtain a record of variations from a standard plane or cylinder. In such cases the skid is not used but the stylus is guided in a straight line by a slide incorporated in the instrument or by a radius attachment which gives a circular motion. These devices are provided in the "Talysurf" instrument of Taylor, Taylor and Hobson. In this apparatus the motion of the stylus parallel to the surface is increased 200 times in the record, and movements perpendicular to the surface are magnified from 2,000 to 40,000 times. These figures must not be forgotten when the records are considered, otherwise an entirely wrong impression of surface quality will be received.

Graphs of Typical Surfaces

Fig. 199 shows the contour of a diamond-turned surface. The actual length of surface traced in the graph is one-fiftieth of an inch

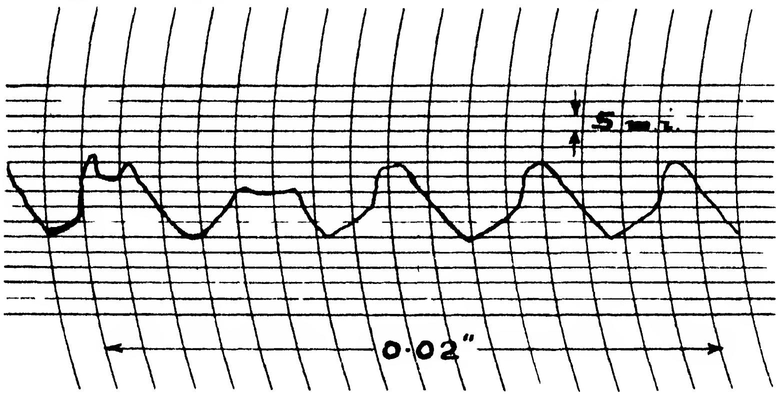


FIG. 199.—Diamond-Turned Surface.

and the maximum depth of the contour from crest to root is slightly less than 0·00004 inch or, as it is usually put, 40 micro-inches, the micro-inch, or one millionth of an inch, being a convenient unit for these small quantities. The waves arising from the traverse feed of about four thousandths of an inch per revolution are very clearly marked. Imposed on these are smaller waves which may be derived from the outline of the tool and complicated by vibrations of the work and machine, that is, by a minute kind of chatter effect.

A ground surface is shown in Fig. 200 in which the maximum crest to root depth is 50 micro-inches, as would be obtained by fine grinding. Ordinary grinding would give much greater variation than this, but

the sharply peaked form is characteristic of grinding. There are so many variables in this process that it is almost impossible without knowledge of the particular conditions to relate the irregularities shown by the graph to the factors which have caused them. Among other

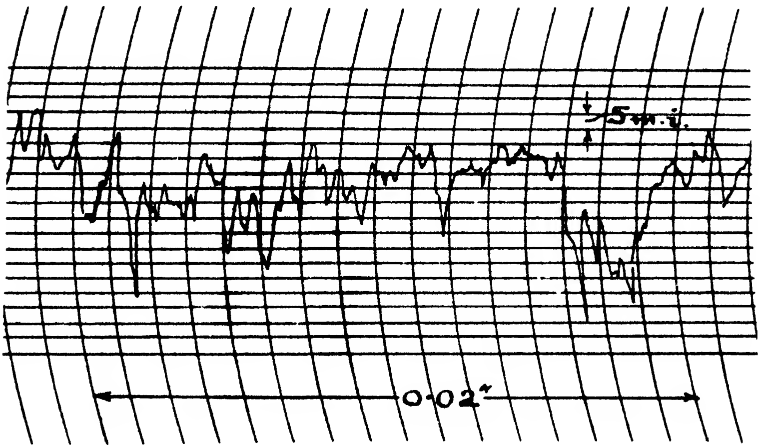


FIG. 200.—Ground Surface.

things, there are the random disposition of the grains in the wheel, the changing phase relationship between the revolving wheel and the revolving work, movements of both axes in their bearings and vibrations of sundry parts of the machines The possibilities are very

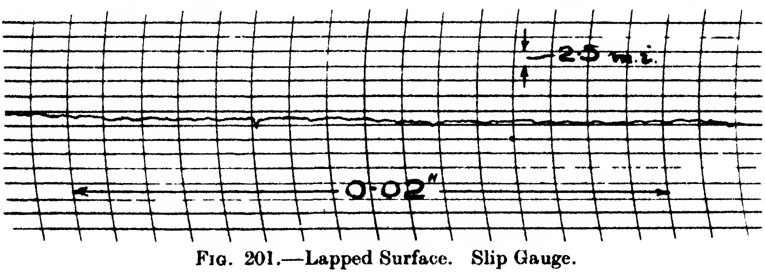


FIG. 201.—Lapped Surface. Slip Gauge.

numerous, and in general one may trace some waves related to the traverse feed and some to the grain size, but not very much more without details of the conditions under which a particular record was made.

For comparison with the previous figure, a graph of a lapped slip gauge surface is given in Fig. 201. Here much less regularity is seen, as might be expected, since both the arrangement of the abrasive

particles and the relative direction of motion of work and lap are more erratic than in grinding. The vertical scale in this figure is double that of Fig. 200, namely 40,000 to 1, this magnification being required to show the smooth surface which is produced by careful lapping. The maximum variation in depth is a little less than 4 micro-inches. Even after making due allowance for the distorted scales, it is obvious from the last two figures that the preference for lapped rather than ground finish for gauges and similar exacting requirements is well-founded.

Numerical Specification of Surface Finish

Although the graphs, as discussed above, are most useful for the investigation of the contours of surfaces, they are not suitable for ready application in the workshop. There is consequently a demand for a numerical method of specification, preferably by a single number. No such simple method has yet been evolved which is completely suitable for general application, and it is doubtful if it can be. What is desired for workshop inspection is a device which can be applied almost as readily as a limit gauge to determine whether a surface is within certain specified limits of finish. The quantity to be gauged is much more complex than the single dimension with which a limit gauge is concerned. For example, is the pitch of the undulations or their amplitude of the greater importance? It may be that neither should be ignored. Some wave-lengths may be of greater consequence than others. Again, two surfaces having the same depth from peak to root might have very different contours. Obviously a number depending solely upon the maximum depth would have little relation to the effectiveness of the parts in use. In spite of the difficulties, surface meters have been produced which will give a numerical reading and, provided the number is used with a due sense of its limitations, it can be of considerable value in helping to maintain a required quality. The instrument from which the graphs of Figs. 199 to 202 were obtained is fitted with a meter as well as the pen recorder. The meter gives a reading for the average deviation of a surface from a mean line drawn so that areas between the upper part of the contour and the line are equal to those between the lower part of the contour and the line. This average number may be misleading if surfaces finished by different processes are compared, but if applied to surfaces of similar form is found to be quite useful.

Very similar remarks might be made on the root mean square value

obtained from some American instruments. There is a difference between the average and the root mean square for the same surface, but it is not very great in cases found in practice, and comparisons made on the same range of specimens by the two meters would not differ materially. It is a defect of either number that it fails to distinguish between the quality of differently shaped surfaces, for instance, a sharply ridged surface formed by parallel semicircular grooves might give the same reading as an almost flat surface interrupted by occasional deep scratches, yet the second would obviously have far more effective area and would wear proportionately better. Although the average or root mean square number may be misleading when applied to unlike forms of surface, it is quite useful for comparing surfaces finished by the same process and therefore having similar contours. Its simplicity and the ease by which it may be obtained as a direct meter reading are strongly in its favour as a method for shop inspection, especially if it be checked periodically by a graphical record.

A more complex quantity is known as the form factor which is derived by dividing the metal area above a base line passing through the roots of the contour shown on a surface graph by the total height of the contour from root to crest. When drawing in the root and crest lines it is usual to disregard any extreme values which occur but rarely. The form factor is evidently the ratio of the metal in the contour section above the root line to the total area between the root and crest lines. It may vary from about one-fifth for the grooved surface mentioned above to nearly unity for the other surface with occasional scratches. In a particular case, a ground surface gave a form factor of 0·5, and by careful lapping the surface was changed to give a factor of 0·9.

Fine Finishing Processes

Although by the aid of very careful manufacture, fine turning and grinding machines can be made to produce surfaces having an average meter reading within 6 micro-inches, other processes are more commonly used for such fine finishing. One of these, lapping, has already been discussed in the previous chapter. Others, of more recent development, are honing and super-finishing. They are in some respects similar to lapping and they are both used to refine ground surfaces by means of blocks of bonded abrasive shaped to conform to the work. In both processes the motion of the blocks over the work is arranged

to eliminate the parallel grooving left by the wheel and to substitute either very finely cross-hatched or randomly scratched surfaces. Honing gives a fairly uniformly fine cross-hatching as in the case of a cylinder bore where the relative motion is a combination of rotation with axial reciprocation. Superfinishing combines rotation with rapid oscillation and a traverse motion, the effect being to change continually the relative positions of the stones and the work. A superfinished surface shows very fine scratches erratically disposed over a smooth background.

The essential differences between lapping, honing and superfinishing will be clear from the following brief comparison of the three processes. Lapping is done at a relative speed of the work and lap varying between 30 and 90 feet per minute, the motion being such as to vary continually the disposition of the work and the lap. The pressure varies from 10 pounds per square inch up to 500, being heavier in machine than in hand lapping.

Honing of cylindrical parts employs a rotary speed of 150 to 500 peripheral feet per minute with an axial reciprocation such that the successive paths of the hone intersect each other at about 40°. The pressure varies from 500 to 1,000 pounds per square inch.

Superfinishing is done at a low relative speed, usually between 5 and 60 feet per minute, and under very light pressure, which is from 1 to 30 pounds per square inch. It is an important feature of the process that when the surface irregularities have been worn down and contact is almost complete over the whole area, abrasion automatically ceases on account of the low intensity of pressure, and no further change takes place no matter how long the motion is continued. This is because the abrasive blocks are then floated on a complete film of lubricant.

Meter readings as low as 1 or 2 micro-inches may be obtained by all three processes. It is a common characteristic that the readings are independent of the direction in which they are made, unlike those from turning or grinding which give very different figures along and across the direction of cutting.

The Effect of Improved Finish

When the height of the irregularities in moderately well-finished work is compared with the tolerances allowed on dimensions, some doubt may be felt as to the need for the very fine finishes which are now specified for certain classes of work. In the discussion which

follows an attempt is made to find an answer to this doubt. Considering the journal of a shaft which is to be a very close fit in its bearing, a tolerance of three ten thousandths of an inch may be required. The minimum clearance may be three ten thousandths of an inch, and a tolerance of five ten thousandths of an inch may be permitted for the bearing. These figures mean that satisfactory assemblies may have a diametral clearance varying from 0·0003 inches up to 0·0011 inches. Expressed in micro-inches these quantities are 300 and 1,100 respectively. In fact the permissible range of clearance would be greater than this, because even with the maximum initial clearance there would still be some allowance for wear. Comparing these figures with the root to crest height of a good ground finish, which would be about 60 micro-inches, it is clear that the wear necessary to reduce the ground surface to perfect smoothness, namely 120 micro-inches on diameter, is not very considerable, and would not by itself entail a very great reduction in the life of the part. Evidently the advantages claimed for finer finishes cannot be entirely derived from the gain in effective size. Experience and experiments suggest that it is rather a consequence of the elimination of high places which cause intense local pressure and rupture the film of lubricant. When this occurs, metallic contact between the journal and the bearing ensues and causes local heating and rapid wear and in extreme cases momentary seizure and tearing of the working surfaces. If the latter effect happens, it prevents the formation of a complete smooth surface on either member and the cycle may be repeated. Hence not only will the rate of wear be initially augmented but wear will continue beyond the level which would suffice to remove the high places under easier conditions, since a stable surface condition may not be developed. The necessity for "running in" new machines at moderate speeds and loads arises from the initial roughness of working surfaces which must be refined before full load conditions can be endured. Experience of more highly finished surfaces shows that they permit machines to withstand full load conditions without the preliminary running-in process, as in car engines with superfinished surfaces. Schlesinger mentions the case of a diamond turning lathe with a fine ground nitrided spindle 2 inches in diameter running at speeds up to 3,000 revolutions per minute. This spindle gave trouble as first assembled. It was then lapped to an average roughness of 11 micro-inches and still ran hot. After a second lapping, which reduced the roughness to 5 micro-inches, it ran satisfactorily and at a much lower

temperature than before. Improvement in the finish of journals and bearings permits the use of less viscous lubricants and as a result the reduction of the clearance, which is a considerable advantage in cases where the position of the axis of a spindle must be closely controlled as in machine tools. From experiments on the resistance of bearings to seizure under heavy loads, W. E. R. Clay found that the limiting loads for various journal finishes varied from 2,165 pounds per square inch for a ground journal of 20 micro-inches up to 4,800 pounds per square inch for a fine lapped journal of 1·4 micro-inches. Intermediate values for journals with other kinds of finish are found to depend very closely upon the smoothness of the surfaces.

A further possible explanation of the advantages gained by smoother finishing may be found in the less destructive effect, in comparison with grinding, of processes akin to lapping. The action of a grinding wheel, depending on high speed and intense local pressure, produces very high temperatures, and although these are only local and momentary, a layer of injured metal particles is caused to flow over the surface. This flowed layer, sometimes called fuzz metal, has less enduring properties than the original crystalline structure and may be insecurely attached to it. The result is that by the time a satisfactory working face is formed upon a ground journal the clearance may be increased by the thickness of the flowed layer in addition to the depth of the surface roughness. Like roughness, it can be removed by abrasion at low speed and low intensity of pressure, hence the effectiveness of superfinishing or lapping.

Causes of Surface Roughness

Until surface graphs have been studied more fully and with full knowledge of the conditions under which they were drawn, attempts to assign causes to the waves of particular graphs must be largely speculative. Meanwhile the following remarks are made with the reservation that they refer to factors which exist in some cases, although they may not even then be the principal cause of roughness. In any machine tool with a revolving spindle there may be changes in the position of the axis of the spindle as the thickness of the supporting film of oil varies in response to variations in pressure on the cutting tool. The variations in cutting pressure being of a recurring or pulsating nature may also cause vibrations in various parts of the structure of the lathe. In extreme cases these vibrations cause the well-known chatter and the results are obvious without the aid of

special instruments. Even when less apparent they may show as an undulation in a surface graph traced in the same direction as the cut, i.e. around the circumference of the work. Inaccurate slides will usually cause waves of long periods, too long to be recorded on the greatly amplified graphs given by the surface meters, in which one inch may represent a surface length of as little as one two-hundredth of an inch and not often more than one-quarter of an inch. Such errors in slides should be found by other tests, e.g. the auto-collimator, and eliminated before fine surface measurements are attempted.

Spindles supported in ball or roller bearings may cause a complete wave in the work once in two complete revolutions. This will cause an undulation parallel to the axis and of a pitch of twice the rate of feed per revolution, and is due to the presence of one ball or roller in the bearing having a diameter slightly larger than the rest. Unless the parts of the bearings are very carefully selected this is likely to happen, and the action would be equivalent to that of an eccentric bush between the bearing and the journal rotating at half the speed of the shaft. Out of roundness of an over-size ball or roller would introduce a further irregularity of a frequency depending on the relative diameter of the journal and the ball or roller.

The surface of ground work is even more complex than that of turned work. The feed marks are less distinct since they are caused by an enormous number of randomly placed cutting points and not by a single cutting edge. In addition to these and to those which are due to the float of the work spindle and vibrations in the machine there may also be waves arising from the grinding wheel spindle and its bearing. The effect of a badly balanced wheel is too well-known to need particular mention, but even with a perfectly balanced wheel, variations in the thickness of oil-film in the bearings may cause the axis of the spindle to move around in a more or less circular path. The change in the note produced by the diamond used to true the wheel may be traced to this cause.

Some years ago ball-bearings were considered unsuitable for the highest class of external cylindrical and surface grinding as they were found to cause a ripple which was very obvious in the highly reflecting ground surface. Consequently, in spite of their inherent troubles, closely fitted plain bearings continued to be used with modifications, such as reduction of clearance in conjunction with the use of oil of low viscosity (kerosene has been used by some designers).

Since that time both plain and ball bearings have been improved.

It is well known that the parts of standard commercial ball bearings are made within very small dimensional limits. But even these small tolerances are much greater than the irregularities permissible in highly-finished surfaces. Realising these facts, Messrs. Boneham and Turner of Mansfield have designed and produced a range of spindles for grinding and fine boring which are capable of producing work with an average surface quality within 4 micro-inches and with a maximum depth of 20 micro-inches. These excellent results are achieved by extremely precise manufacture and careful selection of the components of the bearings. Mist lubrication is provided and dust is excluded by a system of revolving baffles. The spindles are preloaded in such a way that expansion is taken up at the end remote from the work or grinding wheel. Although these ball-bearing spindles

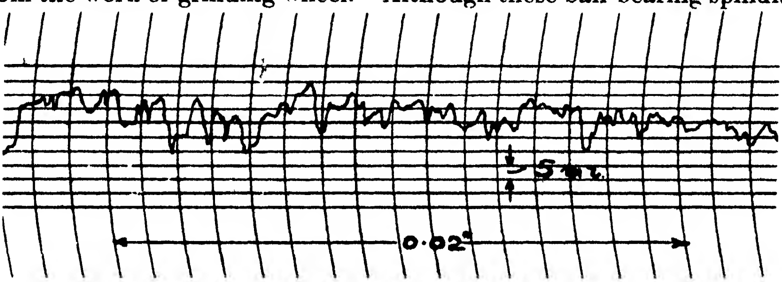


FIG. 202.—Fine Ground Surface.

were originally made to overcome the disadvantages of plain bearings for the high speeds necessary in internal grinding, they have been found equally satisfactory for external and surface grinding. A surface finish record obtained from the external grinding of hardened steel is shown in Fig. 202.

The fluid lubricated bearing has also been improved. This has been accomplished by the substitution of Michell pads for the plain cylindrical sleeve. In the design manufactured by Cincinnati Grinders, Inc., the journals of the spindle are supported on five pads, the resultant oil pressures on which act radially on the journal and resist any tendency to displacement of the axis. It is essential for the success of the device that a full and regular supply of oil should be provided. To ensure this, the spindle and bearing assembly is kept under positive oil pressure and means are fitted to eliminate any air from the oil system. It is claimed for this design that the float or lateral movement of the spindle has been reduced from about 60 micro-inches to an amount which is almost imperceptible.

Much progress has already been made in the examination of surface finish and its influence on the subsequent service obtainable from the finished components, but it is likely that further research may enable the desirable limits for surface meter readings for various purposes to be specified with more certainty. There are at present conflicting opinions as to the advantage of extremely smooth surfaces for some applications, and the relative importance of long and short wave irregularities still remains a subject which will repay investigation. Attention tends to be concentrated on the short wave or fine texture, but it is by no means certain that the effect of longer waves should be overlooked.

CHAPTER XV

MEASUREMENT AND GAUGING

Plane Surfaces

THE plane surface is fundamental in precise machine work. Machine tools themselves are assemblages of plane surfaces disposed in such a way as to guide a cutting edge in a selected path over the work to be machined. Whitworth appreciated the importance of the plane surface and much of his pioneer work was directed to the production of planes for various purposes, either as machine tool elements or in connection with his system of gauges and measuring machines. The principle on which he worked to produce standard planes or surface plates is still followed even in the manufacture of the almost perfect planes known as optical flats.

Whitworth's problem was to produce plane surfaces and to test them in the absence of any standard of comparison. He devised the now well-known plan of scraping plates in sets of three, until the plates of each possible pair fit together.

The test for flatness is comparison with a plane surface, but the standard plane is developed as part of the process. When the three plates fit together in any possible pairs each of them must be plane. Whether the standard is produced at the same time or not, comparison with a standard plane is still the method of testing surfaces which are intended to be plane.

One method of testing is to coat the standard plate with a thin film of colouring material. Red lead and oil used to be very common, but oil colour such as Prussian blue is more convenient and gives a more definite mark. This test shows up the high places, and indicates the proportion of the area which is within, say, one-quarter thousandth of an inch of the highest level, but does not give any information as to the depth of the hollows. Some idea of this depth may be obtained by the use of small slips of known thickness. When such a slip is placed in a depression which is too shallow for it the upper plate will swing freely about the slip. A few trials with various known slips will give a good idea of the depth of the unmarked places. The

use of thin paper slips at intervals between two plates or between a straight edge and a surface to be tested gives a very good idea of the coincidence between the two. Very small variations in level are shown up distinctly by the relative tightness with which the slips are gripped.

In the absence of a standard plane it is possible to test the flatness of a plate by means of a sensitive spirit level, using the fundamental method developed by the National Physical Laboratory. The level is mounted on two ball supports placed close together and is moved step by step over the surface of the plate so that after each movement the second support takes up the position previously occupied by the leading support. If the level has been calibrated the bubble deviations can be converted into differences in height of the two points of support. For a tube of radius about 83 feet resting on points 1 inch apart, a deviation of the bubble equal to one-tenth of an inch indicates a difference in height of the supports equal to one ten thousandth of an inch. Repeated applications of the process will enable a series of profiles of the surface to be plotted, the height of each successive point being determined in turn from the last one established. By using a tube of longer radius or by placing the support points closer together proportionately smaller differences in height may be indicated.

Another method of examining a surface plate which not only indicates the position of the high places but enables the depth of the hollows to be measured depends upon the use of a scribing block and a dial gauge or similar measuring device. The plate is set up beside the standard plate, both being levelled. The scribing block with dial gauge mounted so as to overhang at one side is placed on the standard plate, and the dial gauge brought into contact with the other plate. If the block be then moved over the standard plate variations in level of the other plate will be shown by the gauge reading. By following a series of regular paths a contoured plan of the plate can be drawn. The standard plate may be either scraped or lapped, provided it is of fairly good quality, because the area of the block should span a number of the high spots and should therefore not be affected by the scraped hollows. If a lapped plate is used it may be necessary to coat it with a very thin oil to prevent the block wringing to it, otherwise a sufficiently free motion may not be possible. Complete contact is never attained by scraping, but may be attained by rubbing or lapping the plates together.

Interference of Light used to Test Surfaces

When surfaces are very nearly flat and are highly polished, as they may be after lapping, it is possible to test them by comparison with an optical flat. This method depends on the interference between light waves reflected from two closely adjacent surfaces. It was in common use by optical manufacturers long before it was applied to engineering productions: A great advantage of the method for definite measurement is that it shows directly the contour of the surface tested. Monochromatic light transmitted through the flat B, Fig. 203, is reflected partly from the internal lower surface of the flat and partly from the upper surface of the piece to be tested. That part of the light which is reflected from the work has obviously to travel through a slightly greater distance than that which is reflected from the inner face of the flat. According to the distance between the two faces, that is, according to the variations in level of the work, so the two pencils of light return more or less out of phase. If they are exactly opposite in phase at any place no light shows there. As the distance changes they gradually come into phase and a band shows. Fig. 204 shows the effect which appears when an optical flat is made to rest at a very small angle on a plane metal reflecting surface. A

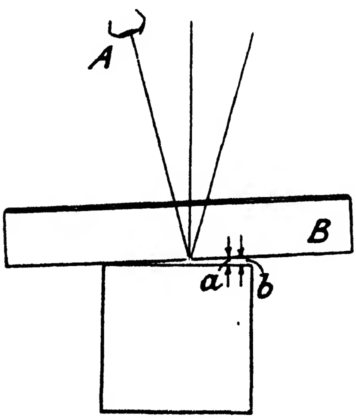


FIG. 203.

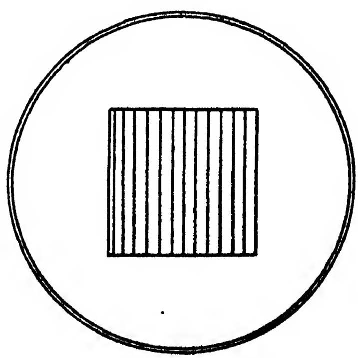


FIG. 204.

number of equally spaced straight dark bands, *a*, *b*, are seen by an observer at A, Fig. 203. These occur at positions such that the two reflected rays are opposite in phase. Between them there are bright bands where the two rays return in phase. The difference between the distances *a* and *b*, Fig. 203, is one-half of the wave length of the

light used. If the mercury vapour lamp be used the wave length is 0·0000216 inch, and the difference in level indicated between two adjacent light bands is approximately one hundred thousandth of an inch. The test is too delicate except for surfaces which are very nearly perfect, such surfaces, for instance, as those of high quality gauge blocks. It is, however, very useful for cases within its range,

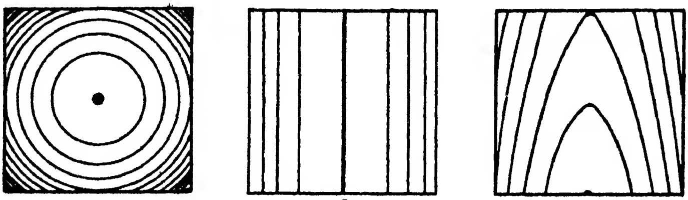

(a) (b) (c)

FIG. 205

especially as it gives a contour diagram of the surface. Each continuous dark band follows a part of the surface which is at a constant distance from the flat. Fig. 205 shows in (a), (b) and (c) typical diagrams for a spherical surface and two cylindrical surfaces respectively. Care should be taken if the mercury vapour lamp be used for this purpose to make sure that the ultra-violet rays are screened from the eyes as they are likely to cause injury. With the light from a mercury vapour lamp passed through a green filter interference bands can be observed even when the surfaces are separated by a quarter of an inch or so.

A compact arrangement of optical flats and a coloured screen to give nearly monochromatic light from ordinary daylight is made by Adam Hilger. There are three flats, so that the apparatus is self-checking.

Length Measurement

After flat surfaces have been made and verified it becomes necessary to determine distances from surface to surface and the angles between surfaces. The measurement of distances is one of the most elementary of machine shop problems, and it is also at times one of the most difficult. In some of the more elaborate gauge making it is often very troublesome to know how nearly the gauge approaches the specified dimensions. This is especially so in the case of form or outline gauges, and is usually the hardest part of such gauge making.

Given definite knowledge of the excess metal and its location it is fairly easy to deal with it. Some years ago the question of measurement was in a more uncertain condition in most shops than it is today. There are now readily available for general use many measuring devices which were not found at that time outside the laboratory or perhaps a few of the instrument-making shops.

Line and End Measurement

There are two principal methods of measurement in use, namely, that one which depends upon contact of measuring faces with the object, and that other in which there is no actual contact with the object but the part concerned is aligned with a scale or other standard by means of a collimator. Before Whitworth introduced his standard plugs and rings shop measurements depended upon the graduated scale, either directly or by way of calipers. The calipers in hands of average skill could not be set with certainty within, say. two-thousandths of an inch. In order to fit parts, for which this might not be near enough, it was usual to finish one member and to set calipers from this for measurement of the other member. By this means much closer work could be done than was to be relied upon if scale settings had been used. That is to say, the closeness of the fit was very near to that specified, although the exact dimensions of either member could not have been stated within some thousandths of an inch of an absolute size. Thus the more precise sizes were found by contact, and this principle was followed by Whitworth when he introduced his system of plug and ring gauges. The contact method is still the one preferred in the largest proportion of shop measurements. Even where optical devices are used to obtain the reading there is most usually contact with the work.

Precise End Blocks

Allowances for fits were made by estimation when standard gauges (plugs and rings) were used, but the later developments of block gauges introduced by Johansson enable all sizes throughout a wide range to be built up in consecutive steps of one ten-thousandth of an inch. In Johansson's full set of gauges there are eighty-one pieces, although that number is more than is essential to provide all the steps of 0·0001 inch within the range. The additional gauges simplify the choice of gauges for building up and permit the gauges to be

checked by comparison of various combinations giving the same total lengths.

In the set of eighty-one gauges there are the following series :—

Series 1 : 9 pieces. 0·1001″ to 0·1009″ in steps of 0·0001″.
Series 2 : 49 pieces. 0·1010″ to 0·1490″ in steps of 0·0010″.
Series 3 : 19 pieces. 0·0500″ to 0·9500″ in steps of 0·0500″.
Series 4 : 4 pieces. 1·0000″ to 4·0000″ in steps of 1·0000″.

From these gauges any size expressed in ten-thousandths from 0·2000 inch to 10 inches can be built up. They are finished to such a degree of flatness and polish that they will wring together and will adhere strongly enough to be handled. Under favourable conditions as much as 70 pounds per square inch of surface is required to separate gauges which have been wrung together, although much higher values have been recorded. The film of liquid which is necessary for wringing is so minute in thickness that it may be disregarded for such measurements as are likely to be needed in shop practice, even for checking limit gauges. The film varies but little with the kind of fluid, whether thin or thick oil, and is of the order of one-millionth of an inch. Johansson gauges are made in four grades of accuracy although the highest grade is beyond most requirements. The four grades are approximately of the following orders :—

AA + 2 parts in one million.
A + 4 parts in one million.
B + 6 parts in one million.
C + 8 parts in one million.

Some care would have to be exercised to avoid using many gauges to form a given combined length in the case of the AA grade, but for the other grades the wringing films are well below the variations permitted in the gauge sizes.

Accessories for Use with End Blocks

The accessories which are available for use with these gauges very greatly extend their range of applications. The base block and scriber attachments which permit them to be built up and used as a scribing block have already been described on p. **51**. Other useful accessories are the extension jaws which may be wrung to a pile of blocks and convert them into snap or internal gauges. Holders are made which can be clamped over the pile of blocks and the extension pieces. They are not intended to take the place of the wringing action, but merely to prevent the accidental separation of the gauges when they

are in use as a combination for some considerable time. The gauges should always be wrung when used in combination, as this ensures that the thickness of the films between them will not exceed the small quantities mentioned. It also provides a safeguard against the employment of damaged gauges. A gauge which is scratched so that a burr projects above the finished surface will not wring to another, consequently any gauge which fails to wring must be regarded with suspicion lest it should have been injured in some way not otherwise noticeable.

Although the Johansson firm was for many years the only one which manufactured this kind of gauges, and their particular method still remains secret, gauge blocks of similar quality are now made by at least two other firms, the Pitter Gauge and Precision Tool Co. in this country, and the Pratt and Whitney Co. in the United States of America. The method used by the former company was developed at the National Physical Laboratory, and that used by the latter at the United States Bureau of Standards.

Both firms supply accessories for use with their gauge blocks which fulfil the same purposes as those described above in connection with the Johansson gauges.

Contact Pressure in Measurement

For measurements within one-thousandth of an inch by contact some delicacy of touch is required, even with a micrometer. Three or four men measuring the same cylinder gauge with a micrometer may all obtain different results even though they may all be experienced. The differences, which may be only two or three ten-thousandths of an inch, are caused by the different contact pressures used in screwing the micrometer on to the work. If they were supplied with a standard cylinder or micrometer check they would all apply a different correction to the micrometer and would then give results very closely in agreement on remeasuring the original plug. Each individual tends to use a contact pressure peculiar to himself, which he will not vary.

When definite results to one ten-thousandth of an inch are wanted some form of indicator must be used to register zero when the pressure is correct. With this aid any number of observers will return the same readings on a given measurement. Pressure indicators have been regularly fitted to measuring machines ever since Whitworth made a machine for the measurement of his standard gauges. They

frequently depend upon the compression of a spring to a point determined by a device which greatly magnifies the motion of the spring-controlled measuring face, so that a very definite indication of the amount of compression is given. With the growing desire for close measurement in the shop, certain makers fit micrometers with an indicator which must be brought to zero before taking the reading, thus eliminating the effect of individual variations.

Limit Gauges

The micrometer and similar appliances are measuring instruments as distinct from gauges. A measuring instrument gives the size of a part in terms of some unit, more or less closely according to its design. But a gauge merely decides whether a part is a given size or not, or if it be a limit gauge, whether the part lies between the two sizes embodied in the gauge. For repetition work the gauge is more useful than a measuring instrument, since it is more quickly used, and in the limit form relieves the operator of the burden of deciding whether the work is near enough to size. Limit gauge systems are discussed more fully in the next Chapter. There is, however, one point which must be mentioned here in connection with the use of limit gauges. The " Go " gauge should check as many elements as possible, but the " Not Go " gauge should be limited in its application to one element only at a time. For example, a circular shaft might be gauged by two ring gauges which would be a sufficient check if it were known that the shaft was circular. But if it should happen that an elliptical shaft were presented it might pass inspection by ring gauges, provided its major diameter were smaller than the larger gauge diameter and greater than the smaller gauge. There would be no safeguard against the minor diameter being below the minimum diameter specified. In fact, a flat strip of metal of width between the limiting diameters could pass the ring gauge test, although it would of course be obviously wrong. The above is merely quoted as an example, and it is not suggested that two ring gauges would be used as limits for a shaft. In practice, two snap gauges are used for the sake of convenience, because a snap gauge need not be slipped over the end of a shaft and is therefore applicable to reduced diameters beyond collars, etc.

If it were not for that difficulty a ring gauge for the " Not Go " and a snap gauge for the " Go " size would be a better combination, since the ring gauge would detect departures in excess of the circular

form, such as occur in the lobed figures of centreless grinding, while the snap gauge by several applications would detect any deficiency in size. Many other examples might be given, but the principle is simple. The " Go " gauge should check the maximum metal sizes, not only separately but in their relation to each other, therefore it should cover the full outline. The " Not Go " gauge should check the minimum metal sizes and should not pass work which is up to size in some dimensions and below size in others, therefore it should gauge single dimensions only, even though it may have to be applied several times.

Angular Measurements

The simplest case is probably that of surfaces at 180° to each other, that is, parallel. This can be checked by linear measurements at several points. There are other cases where angles can be most conveniently and accurately measured by means of lengths. The sine bar in its numerous forms exemplifies this. It varies from a small strip of hardened steel about 1 inch by ½ inch by 6 inches long up to comparatively heavy fixtures weighing a quarter to half a hundredweight. The principle is the same in either case. It permits the accuracy of gauge blocks to be used in setting and measuring angles. Fig. 206 shows a simple sine bar. The two cylinders are equal in size and are set in this particular case at a centre-to-centre distance of 5 inches. To set the bar at an angle of, say, 30° to the plate one roller may rest on the plate, the other must be raised on a stack of blocks of a height equal to :

$$5 \times \sin 30° = 5 \times 0{\cdot}5000 = 2{\cdot}5000''$$

The decimal is continued to four places, because with the blocks it would have been possible to obtain the size to a ten-thousandth of

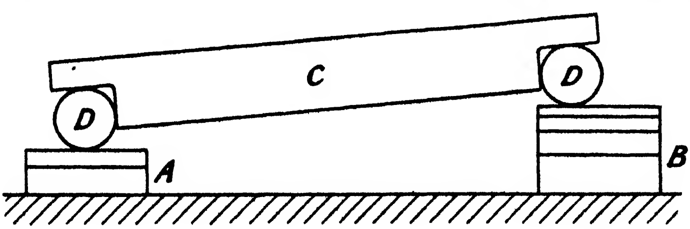


Fig. 206.

an inch. A difference of this magnitude would only cause an error of five seconds.

Sine bars are very handy for gauging taper parts. As a readily fitted device, a sine bar may be set out from the vertical face of an angle plate on distance pieces. The bar is set up on two piles of blocks from the surface plate on which the angle plate stands.

The Taft Pierce Co. make a very convenient form of sine bar suitable for many applications. It is mounted on a vertically slotted bracket from a substantial plane base. To enable angles which approach 90° to be set without loss of precision there is a right-angle extension at one end of the bar. Angles over 45° are set by means of their complements. For example, to set an angle of 60° the long arm of the bar would be set to 30° in the usual way. The short arm would then stand at 60° more accurately than if an attempt had been made to set 60° directly. Several applications of the sine bar are given in Chapter V.

As a rule it may be said that the sine bar is more precise for angular work than the graduated circular tables or bases of machines. One degree at a radius of 6 inches corresponds to slightly more than one-tenth of an inch and, with the marking usually found on machine tools, should be subdivisible into fifths, *i.e.* to about twelve minutes of arc. With a 10-inch sine bar an angle may be set to two and a half seconds. The vernier protractors made by the Brown and Sharpe Co. and Starrett may be read, or set, to five minutes. This instrument has a graduated circle about 3 inches in diameter.

The Johansson Co. have introduced a set of angle gauges or templates which enable angles over a wide range to be built up in steps of one minute. The principle involved is somewhat like that of the

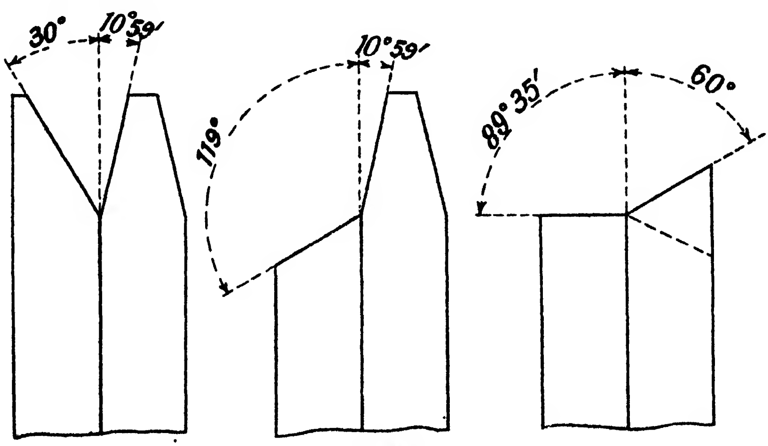


FIG. 207.

same firm's block gauges. There are eighty-five pieces in the set, made up in series thus :—

First Series (minutes)—

Fifteen pieces each giving four angles, the whole covering all angles from 10° to 11° in increments of one minute.

Second Series (degrees)—

Forty pieces covering all angles from 0° to 90° in increments of 1°.

Third Series (minutes)—

Thirty pieces, each giving two angles, the whole covering all angles from 89° to 90° in increments of one minute.

The long sides of all the slips are lapped to fit so that the gauges can be built up in pairs as shown in Fig. 207. The whole set covers all angles from 10° to 350° in increments of one minute, and angles from 0° to 10° and from 350° to 360° in increments of 1°.

The use of discs for setting and measuring angles has been referred to on pp. 70 to 72, and scarcely needs further amplification.

A very interesting and useful set of gauges for angular measurements has been devised by the National Physical Laboratory and is made by the Coventry Tool and Gauge Company. The standard set B consists of three series of angle pieces with opposite faces lapped to contain the following angles :—

Series one : 1, 3, 9, 27 and 41°.

Series two : 1, 3, 9 and 27 minutes.

Series three : 0·1, 0·3 and 0·5 minutes.

With one additional 9° piece it is possible to build up all angles from 0° to 90° in increments of 6 seconds. The gauges are eleven-sixteenths of an inch by three and five-eighth inches on the wringing faces and are made correct within 2 seconds for set B and within 1 second for set A. In conjunction with a precision square plate which is part of the set, the angle gauges may be applied to a dividing head for circular dividing. The square plate is mounted on the spindle of the head and combinations of the angle gauges are wrung to one of the faces. Where the axis of rotation is horizontal either a spirit level or an auto-collimating telescope may be used to locate the exposed face of the gauge combination or one face of the square in the desired reference plane. By wringing various combinations of angles to the square, the spindle may be located at any required angle. For dividing on a vertical axis the telescope must be used since the spirit level is not applicable.

The Examination of Forms and Profiles has been greatly simplified in recent years by the introduction of travelling microscopes on a workshop scale and by the development of the projection lantern into an apparatus of reliable accuracy.

The travelling microscope machine made by Alfred Herbert of Coventry is an enlargement of the instruments used in laboratories. It has a sliding table carrying a pair of headstocks for circular work such as screw gauges, or for supporting flat work up to 24 inches by 4 inches in dimensions. The microscope is carried on a compound slide overhanging the sliding table. The micrometer slides give a range of 1 inch in each of two perpendicular directions, measurable by large discs to one ten-thousandth of an inch. There is a secondary cross motion which increases the range covered by the microscope. Longitudinally the work table moves on a vee and flat, and may be set in definite positions by gauge blocks between contacts on the slide and the bed. The bed is made in box section of cast iron, and is planed on all four sides to avoid the tendency to gradual change of form which results from partially clearing the skin off a casting. Three-point support is used so that the bed may not be twisted by being placed on an uneven foundation. Both these precautions are desirable in the case of machine tools and are especially so for a measuring machine. Even an apparently stiff bed may be twisted to an astonishing degree by improper support.

A machine of this sort is used to determine the positions of points in a jig plate, template or gauge by measurements from two perpendicular base lines. The microscope, giving a magnification of fifteen to twenty-five diameters, has cross webs in its eyepiece. The intersection of these webs is brought vertically over the particular points to be checked in turn. These points may be centres for circular arcs or for boring holes, or they may be the salient features of an outline. Curved outlines may be checked by locating a series of points and comparing their positions with those of points calculated from the particulars of the curve.

Another feature of the microscope mounted in this machine is the possibility of rotating the cross webs. They are carried in independent holders and may be turned to lie at any angle to each other. This is useful for measuring the angle between two adjacent sides or faces of a gauge, as, for example, the thread angle of a screw gauge. A graduated circle attached to one web and a vernier attached to the other enable readings to be taken to one minute.

Very elaborate universal machines for co-ordinate measurement are now made by the Société Genevoise and by Carl Zeiss of Jena. They are adaptable by the aid of attachments to a very wide range of fine measurement. Complete descriptions of these machines would occupy much space. It is interesting to note that the provision of such appliances for machine shop purposes is a sign of the changing methods occurring so quickly of late years. It is a consequence of the realisation that precision in making tools, fixtures and gauges reduces costs in large quantity production. Finely divided scales observed through microscopes are commonly used to measure the displacement of slides in the more elaborate machines. This method has the advantage that the measuring elements are not subject to wear. The contacts are, but they can easily be reset. Quite a large number of gauging devices are made which incorporate optical devices for enlarging the measurements. Instruments of this kind are made to read correctly to 0·00005 inch.

Examination by Projection of Image

For the general inspection of outlines the projection apparatus developed at the N.P.L. is one of the most useful which is available to the gauge maker. Until it has been used one can hardly imagine the definiteness and certainty it has introduced into the measurement of gauges and templates. Any shop engaged on fine mechanical work will continually find new applications for it.

As in many other useful ideas, the underlying principle is simple, but a great deal of patient experiment was required to bring its application to the present state of convenience and precision. Essentially it consists of an intense light which is passed through a condensing lens to form a nearly parallel beam, and a projecting lens combination which converges the beam sharply so that it diverges again from a point just in front of the lens. A stage is fitted just behind the projecting lens on which the object under examination is carried. Fig. 208 shows the general arrangement diagrammatically. The most important feature of the apparatus is the projecting lens. This must be carefully made and adjusted in order to produce a uniformly magnified and therefore true image of the object. Given a satisfactory lens, reasonable care in setting the screen squarely with the axis of the apparatus and at the correct distance, will ensure true multiplication. This should be tested by projecting the image of a simple object, say, a small cylinder of known diameter, so that it

falls at a number of positions uniformly distributed over the screen. Measurement of the images and comparison with the known diameter will give the number of magnifications. If this is not constant in all positions it indicates that parts of the screen are either too near to or too far from the lens, if the number is less or greater respectively. For some purposes it may be convenient to use different enlargements. This is easily arranged by moving the screen to or from the lantern. Guide rails on the floor are sometimes fitted to

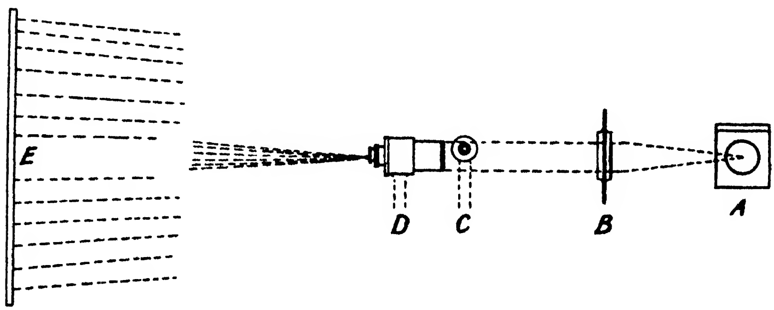


FIG. 208.

permit this to be done easily without impairing the squareness of the setting.

The great advantage of the method lies in the fact that it permits the standard of comparison to be drawn out many times full size—ten, twenty and fifty are often used, although fifty is the most usual. With ordinary care in drawing, the errors should not exceed one-hundredth of an inch, which at fifty diameters corresponds to two ten-thousandths of an inch on the object. Lenses are available which do not introduce any error greater than this, and the definition is quite sharp for sharp-edged objects, such as sheet metal templates or gauges. Articles with rounded edges, for example, screw gauges, cause reflections which show as bright narrow borders round the image. These do not involve any great loss of definition, but may need a little practice to accustom the observer to them. After that it becomes easy to make the necessary allowance.

In a vertical form the projection apparatus is adaptable for measurements of diameters, as in the examination of screw gauges. The

beam of light proceeds vertically past the gauge and is reflected downwards from an overhead mirror to a table on which a profile diagram rests conveniently for inspection. The gauge is carried on micrometer slides and may be moved through known distances to bring opposite sides into coincidence with suitable parts of the diagram. This is a very compact form of the apparatus, but for general gauge and inspection work the horizontal form is the most convenient. As usually made it will cover a field of about 1½ inches diameter, and is easily adjusted to give different magnifications. When a larger object is to be examined it is possible to cover a part first and then to move the object to show the next part, allowing a sufficient overlap to make a connection between one section and the next. The work support is made with a horizontal slide to facilitate the motion of the gauge.

Measurement with Intermediate Contact Pieces

Certain quantities are difficult to measure directly, but are easy to deal with if intermediate pieces of suitable form be introduced

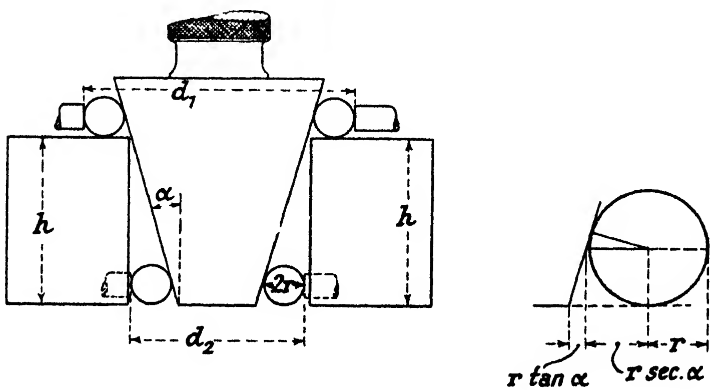


FIG. 209.

between the micrometer and the part. One example of this has already been mentioned in connection with the measurement of spur gears with the aid of cylinders. Another case arises in connection with taper (conical) gauges. These are extremely troublesome to measure by direct contact, and the results are unreliable. The interposition of standard cylinders, as shown in Fig. 209, makes the measurement easy and definite. Two micrometer measurements are taken at a known distance apart along the axis, determined by

the end blocks of height, h. The diameter of the cylinders being known, the taper of the gauge and its diameter at any chosen place, say, at the base, can be calculated as follows :—

$$\text{Taper}=\text{change of diameter per inch of length}$$
$$=(d_1-d_2)\div h.$$

Angle of taper$=2a$

where $$a=\tan^{-1}\left(\frac{d_1-d_2}{2h}\right).$$

The diameter of the gauge at the height of the centres of the small cylinders $=d_2-2r-2r\sec a$.

The diameter at the base$=d-2r-2r.\sec a-2r.\tan a$. The angle of taper gauges can be determined also by a sine bar. Special forms of sine bar are made expressly for this purpose.

Effective diameter measurements on screw gauges are made with the aid of needles or wires by the well-known three-wire method. Two wires are placed in adjacent threads at one side of the gauge and a single wire in the thread opposite. A micrometer reading over the three wires and the gauge, together with a diameter measurement of the wires, which should be all equal, will provide data from which the effective diameter can be calculated. The diameter of the wires should be known within one ten-thousandth of an inch to obtain the full possible accuracy of the method. The calculation given in detail in the Appendix is based on the assumption that the thread angle is correct—this can be verified by a second measurement with a wire of different diameter, or by examination with a projection apparatus.

It is to be borne in mind that measurements such as the above are based on exceedingly small contact surfaces, almost points, and that they are therefore very susceptible to variation by changing the pressure of contact, therefore very light and constant pressure is advisable.

Profile or form gauges must at times be made without the aid of the more elaborate appliances. Although the operation will take longer, they can be set out and checked very accurately with the aid of a sine bar for angular faces and cylinders or discs for the curved parts. Time will be saved if they are marked out in such a way that they can be restored exactly to the marking-out position when the time comes to check them. Standard height blocks and a surface gauge fitted with an indicator then provide a ready means of

comparing the dimensions of edge, which has been shaped to the marked line, with the drawing. The arrangement shown on p. 59 is very suitable for this purpose.

Calculations for Setting Out and Checking Outlines and Positions

There are occasions when it may be necessary to find the positions of the centres of cylinders which make contact with two surfaces machined at a given angle to each other. The line AB in Fig. 210

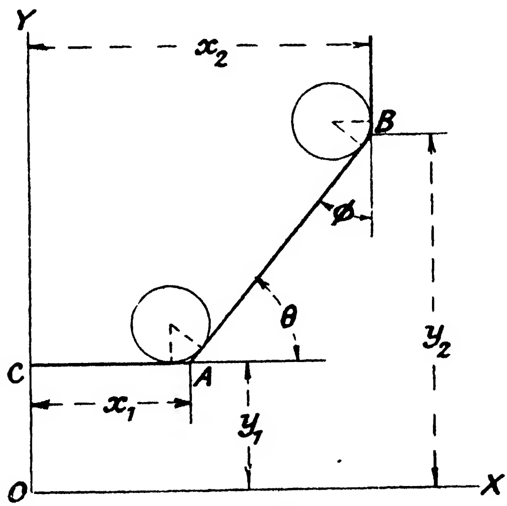


FIG. 210.

is given at a certain angle to AC and of a certain length. Suppose a cylinder of radius r to be placed in contact with AB and AC near A, so that measurements may be taken over it to the reference surfaces OY and OX, the centre of the cylinder is raised by a distance$=r$ above the line AC, and it is displaced also by a distance$=r\tan\frac{\theta}{2}$ to the left of the point A. Therefore the dimension over the cylinder to the edge OX$=y_1+2r$ and the dimension to the edge OY$=x_1 -r\tan\frac{\theta}{2}+r$.

Similarly the dimensions for the cylinder at B are $y_2+r\tan\frac{\phi}{2}+r$ and x_2.

The position of the intersection B may be given in terms of the

angle θ and the length AB. In that case x_2 and y_2 must be found thus:

$$y_2 = y_1 + \text{AB} \sin \theta$$

and $$x_2 = x_1 + \text{AB} \cos \theta.$$

Similar calculations are required when dimensions are given as distances measured along certain angular lines from a centre. These cannot always be used in the machines available. It may be that no circular table is at hand, or perhaps such table as may be used is not graduated with sufficient accuracy. The dimensions must then be converted to rectangular co-ordinates, that is, to dimensions from two perpendicular base lines, one of which is parallel to the base from which the angular directions are specified. An example of such a

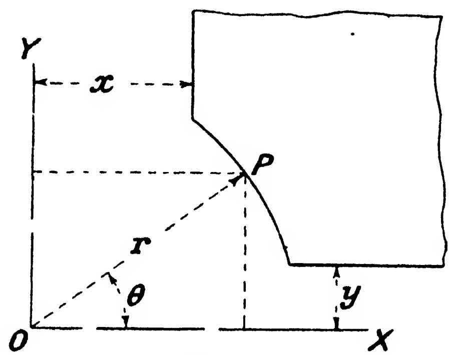


FIG. 211.

calculation is given in Chapter VII, p. 125, in connection with the use of jig-boring machines.

Circular arcs may sometimes have to be plotted, especially in enlarged diagrams for the projection apparatus, because the centres are not accessible or because the radius is too great to permit them to be drawn with the requisite accuracy. Such a case is shown in Fig. 211. Two co-ordinates should be chosen which pass through the centre of the circle. One of them should be parallel to some definite line in the form to be laid out. Radii of the arc should be selected, convenient angles being assumed. Suppose θ is the angle of such a radius to the line OX, then the distances of the point P from the straight sides are:

$$r \,.\, \sin \theta - y$$

and $$r \,.\, \cos \theta - x.$$

Repetitions of this process will enable sufficient points to be found to set the curve out as closely as may be needed.

For rapidly gauging parts which are made in large quantities, any mechanical aid which will increase speed without risk of losing quality is welcomed. Except in the case of very simple parts, completely automatic gauging devices are not much used. Reliance is placed rather on the use of simple appliances which very quickly give a clear indication of size on a very open scale. Constant spring pressure makes the contact, and the indicator is marked with the two limit lines. All parts which cause the indicator to fall outside the limit marks are rejected. From time to time a standard piece is passed between the contact faces, and if necessary the indicator is readjusted. Specially shaped blocks or plates adapt instruments of this kind to many different components. They are better than rigid snap gauges because the contact pressure is constant, whereas a snap gauge applied to a cylinder may be subjected to pressure very much greater than the normal value, and quite sufficient to cause it to admit work which is well above the limit. In the comparator type of gauging device many different multiplying devices are used—compound lever systems, hydraulic as in the Prestwich gauge, and optical as in the instruments with a scale and microscope or modified to project a line of light on to a scale.

Gauging Large Work

References to the exceedingly small tolerances commonly used in the manufacture of small and medium sized components are apt to draw attention away from the relatively smaller and more exacting tolerances specified in large work. A tolerance of $\pm 0{\cdot}0001$ inch on a diameter of 1 inch is relatively of the same order as a tolerance of $\pm 0{\cdot}006$ on a diameter of 5 feet. The latter would be regarded as a very liberal tolerance on much of the work of that size which is done in the heavier engineering trades, yet it is more difficult to work to and requires considerably more skill in handling the measuring appliances. Small gauges are of fairly rigid construction, and if used with reasonable care will give definite results. But gauges to span several feet cannot be made heavy enough to eliminate sag and spring. For one reason, they could not easily be handled, and for another, the cost would be prohibitive, since in large work the cost of the gauge must be carried by comparatively few pieces.

The standard for large work consists of a gauge having a micro-

meter head sliding on a beam or rail and able to be set definitely at any one of a suitable series of complete unit measurements. Subdivisions are obtained by means of the micrometer. This is used to set end rods or trammel gauges for internal and external work respectively. The end rods are usually tubular with one solid end and one screw-adjusting end, often of micrometer pattern. Sag is unavoidable, and is allowed for by supporting the rods or gauges in a definite position and on specified points when they are being set and afterwards using them in an exactly similar way. Wonderfully close results are obtained by such means, which require the application of a kind of skill not called for in small work.

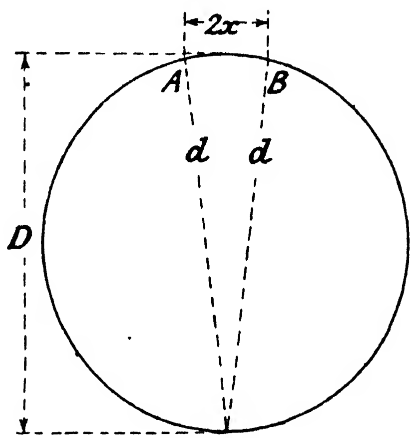


FIG. 212.

Allowances or differences in diameter can be estimated very closely by the method shown in Fig. 212. The gauge is allowed to rock from A to B, and the distance between the contact points A and B is measured. The actual diameter is then calculated thus:

Let d=length of gauge

$2x$=distance from A to B

then diameter of bore$=\mathrm{D}=d+\dfrac{x^2}{2d}$.

This approximation is correct to within one part in a million provided x is not greater than one-twentieth of d.

When using an outside or trammel gauge a thin paper feeler is useful to assist in estimating contact with certainty.

CHAPTER XVI

LIMIT GAUGING AND LIMIT GAUGE SYSTEMS

Requirements for the Fit of Components

In all machines there are parts which must fit together. Some of these fits are intentionally free to allow space for lubrication. Some are close to locate one part definitely on another and yet not so close as to make it difficult to separate the parts when required, others are really tight in order to attach one part securely to another.

When the rule and calipers were the only measuring appliances in use in the machine shop all these fits were made quite satisfactorily, and the machines produced under these conditions were in most cases as efficient as present-day productions. In those days the dimensions of the parts were indicated on the drawing by a single number which was qualified by a note as to the kind of fit required, as running, keying, or press fit. The quality of the fit was left almost entirely to the workman, whose apprenticeship was largely directed to the cultivation of a trained judgment in such matters. If a man's experience had been limited to one class of work it would sometimes happen that he would produce the wrong kind of fit on changing to another class of work. For example, a free running fit on precision work might be equivalent to a close running fit on a rougher kind of work. But, given the right kind of experience, this method of working produced quite satisfactory and efficient machines.

There were, however, several disadvantages attached to it. Most obviously the replacement of breakages or worn parts would involve the making of a new piece to fit the corresponding parts of the machine which would usually have to be returned to the maker for the purpose. Thus there would be much delay in obtaining replacements.

A second disadvantage of similar nature was due to the necessity of making parts one after another in series in order to fit one part to another, with the consequent delay in building a machine.

Finally, there was the difficulty of ensuring the required quality of fit without excessive cost. As a rule the skilled workman is liable to work more closely to size than is necessary. This is probably

because he prefers to spend extra time in fitting rather than run the risk of the machine failing to work.

When machines and mechanisms were needed in large numbers all these drawbacks of the old method became greatly intensified and the advantages of interchangeable manufacture were correspondingly appreciated. Not only were replacements obtainable without delay, but the whole process of manufacture was speeded up and cheapened. When parts are to be made in large batches, methods can be adopted which would not be permissible for single pieces, and even where special methods are not used the saving of time in tool-setting may be enormous.

Basis of Interchangeable Manufacturing

The whole system of interchangeable manufacture depends upon the complete definition of sizes. Take, for example, a shaft and its bearing. A little consideration will show that the man, working in the old way to a single dimension, must have had in mind, even though not consciously, four dimensions. Suppose him to bore out the bearing first. He will aim to make it of the given dimension, but absolute size is not possible. He will therefore take more or less care according to the purpose for which it is required. For a rough job he will be content to get near the size without spending too much time. For a precision job he will take more care and will finish nearer to the specified size. Similarly with the shaft, some clearance must be allowed for freedom and lubrication. This he will keep near the minimum for precise work, but he will allow more latitude for rough work. To emphasise the existence of the four dimensions, suppose the same man to make, say, two sets each of twelve shafts and bearings. One set is to be specified as high-grade work and the other as rough work, but all are to be of the same nominal diameter, say, 2 inches. Careful measurement would show variations in size between the high-grade bearings, but these would all lie within a small margin of the 2 inches. The high-grade shafts would all be less than 2 inches by a very small quantity and, although not all identical in size, would lie very close together. For the rough work the diameters of both bearings and shafts would be scattered more widely from the given size, since less care would have been taken in machining. In each case the resulting fits would be satisfactory for the purpose specified.

The important point is that a skilled man producing fine-grade

work will not keep exactly to a size but will keep within a very small margin of it, which experience has shown him to be sufficiently narrow to ensure the kind of fit desired. Limit gauge systems are an attempt to define such margins, so making generally available the results of many years' experience of all kinds of work.

Limits Defined

In the early days of limit gauges it was not fully realised that such margins existed. There was a feeling that a size was a definite quantity and that any attempts to specify limits of variation must involve a sacrifice of quality by permitting a variation up to the specified limit, a freedom which was thought not to have been previously granted. It was only gradually that limit gauge systems were accepted as merely defining and limiting variations which had in fact always existed. Even now it is possible that the idea of making to absolute size still persists in some shops, not necessarily those in which the most accurate work is done.

The idea of limits seems to have occurred in several countries at about the same time, and various systems were evolved. As they were all based on measurements of actual fits which experience had shown to be satisfactory, it is hardly remarkable that they should have been very similar to each other.

The underlying thought may be illustrated by a consideration of the class known as running fits or, more recently, as clearance fits. Such a fit must have sufficient clearance between the bearing and the shaft to allow free motion, to permit the existence of an oil film, and in some cases to provide for possible differences in the rates of expansion of the shaft and bearing due to temperature changes. This is the minimum clearance for this particular bearing. At the other end of the scale the maximum clearance is reached when the shaft is only just constrained closely enough by its bearing to do its work with certainty. At this stage the fit has reached the end of its useful life. A fit which begins with the minimum clearance and wears until the clearance is the maximum permissible will have its full useful life. This is the ideal aimed at in working to sizes which give the minimum clearance. When tolerances are permitted some part of the useful life may be sacrificed, since the minimum clearance cannot be encroached upon and any variation permitted in manufacturing must therefore be in the direction of increased clearance.

The problem of devising a limit system for clearance fits resolves itself into the best apportionment of the permissible variation of clearance between (*a*) ease of manufacture, and (*b*) the longest possible useful life. Ease of manufacture, item (*a*), is secured by wide tolerances, but these curtail the metal available for wear and so reduce item (*b*), the useful life.

In practice, it has been found possible to evolve an effective compromise between these conflicting conditions for almost all classes of running fits. Workable systems have been devised also for other kinds of fits.

Classes of Fit

Before proceeding to discuss these systems in detail, there are a few terms which should be defined. There are three general classes of fit which have been named by the British Engineering Standards Association (now known as the British Standards Institution) as " Clearance," " Interference " and " Transition " fits. The first named signifies a fit in which there is a space between the two members to allow of freedom for motion, lubrication and possible changes of size on account of temperature variations. In some limit systems this class of fit is referred to as running fits, often prefixed by another word such as " free " or " close."

Interference fits are those in which the inner member is definitely larger than the part into which it fits. Their purpose is to secure one part to another, and in descending order of tightness they have been known as shrink, press and driving fits.

Transition fits are intermediate between clearance and interference fits. They are intended to locate one part in a definite position with regard to another, that is, they are close enough to prevent appreciable motion, but they are not so tight as to prevent dismantling and reassembling. No driving force or torque can be transmitted by these fits, hence when that is necessary a key, or some equivalent, must be fitted. For this reason they have been known as keying fits. Other names sometimes applied to them are push or sliding fits.

As the alternative names for the three principal classes of fits are somewhat lacking in definiteness and have different meanings for different people the B.S.I. recommend that fits should be known by a letter given in the table issued by them. Such letter indicates a definite clearance or interference as the case may be, and therefore leaves no room for misunderstanding.

The definitions of tolerance and allowance given by the B.S.I. have already been stated in Chapter II, p. 10.

Shaft or Hole Basis ?

There are some other terms used in connection with limit gauging which must be explained. When it is decided to make an allowance for a certain kind of fit, if one of the parts be kept to the nominal size the other must be of the nominal size plus or minus the allowance, if we ignore the tolerances for the moment. That part which is kept to the nominal size is said to be the basis member, and the system is said to be on the hole or shaft basis, according to the choice of basis members. Much discussion has taken place for and against the use of each member as this basis. The question is, which member may be more conveniently varied. That is, is it better to keep the hole always near to the nominal size and to vary the shaft to suit the fit desired, or vice versa? In 1906 the Engineering Standards Committee decided that the shaft basis was the more convenient. It is possible that their opinion was chiefly influenced by the heavier classes of engineering, such as locomotive and marine engine building and by millwrighting. In the former, work to be bored is usually finished to size by adjustable tools in contradistinction to reamers by which the size is not easily varied. Thus in large work it is as easy to vary the size of a bored hole as it is to vary the size of a shaft. Hence there is little bias in either direction in heavy engineering. Millwrighting, on the other hand, is more conveniently done if the shaft be taken as the basis member, since shafts are usually obtained finished to size, and it is better to retain this finished size unchanged. The necessary variations are made by adjustment of the diameters of the holes, *e.g.* a larger size for bearings and a smaller size for pulleys. Hence it is easy to understand that the Committee of that date would prefer the shaft as the basis member.

But since the time of that recommendation there has been an enormous expansion of the lighter side of engineering. As a result the bias is now very strongly towards the adoption of the " Hole " basis, since holes of small or moderate size are most easily and cheaply finished to size by means of tools of fixed size such as reamers. This is more especially true when the parts are wanted in large quantities, which tends more and more to become the prevailing condition. On reconsideration, the Engineering Standards Association, which succeeded the Committee, changed the former recommendation, except in the

case of millwrighting. In millwrighting the former conditions still hold. For all other purposes the hole basis is recommended. There is a very considerable saving in tools, since all holes may be made of nominal size within the tolerance permitted, when the hole basis is adopted. The other member is finished by methods in which size is determined by simple adjustments of a machine. It is therefore as easy to finish to one diameter as another, and allowances for various kinds of fit can all be made without trouble.

Unilateral and Bilateral Systems

Having chosen the part which is to be the basis or invariable member of the system, there still remains room for choice in the disposition of the tolerance. In the following discussion the hole basis is assumed. The tolerance may be equally distributed on both sides of the nominal size, in which case the system will be known as bilateral, or, it may be kept entirely on one side of the nominal size, when the system will be unilateral. The early limit systems were nearly all bilateral, or at least an approximation to it, since the tolerance was divided, but not in all cases divided equally. Experience has shown that this system has disadvantages which probably were not at first realised. But, at the time when limit systems were first introduced, the common feeling that latitude was being permitted on work previously held to size would encourage a tendency to keep as close to the nominal size as possible. This would be done by dividing the tolerance so that the mean size of the parts might be equal to the nominal dimension, in the hope that most of the pieces made would be near the mean or nominal size.

It should be emphasised that in any case in running or interference fits one member of each pair of parts must be away from the nominal size, and only the basis member is kept near to it. Growing appreciation of this fact, as limit systems were more commonly used, eventually prepared the way for the introduction of the unilateral system. There were still, however, many opinions in favour of the retention of the bilateral type of system when Sir Richard Glazebrook read a paper on Limit Gauging before the Institution of Mechanical Engineers in 1920. Part of the opposition to the unilateral system was attributable to a desire to keep the basis member as near as possible to the nominal size and part to the more solid reason that a large amount of capital had already been invested in one or other of the bilateral

systems. The latter reason was so important that the B.E.S.A., while strongly advising that all firms installing a limit gauge system after the date of the recommendation should adopt the unilateral system, provided also ranges of shaft dimensions adaptable to the bilateral as well as the unilateral system so that extensions might be provided for. It was hoped that these sizes might bridge the gap between the two systems and ultimately make possible a gradual transition to the unilateral system.

The principal argument in favour of the unilateral system is that of simplicity. It is so important that in the light of present knowledge few firms would now adopt the other system. As an illustration of the difference in calculation between the two systems, suppose it be desired to find the limiting dimensions of a 3-inch shaft and bearing. Let the tolerances be 0·0018 inch and 0·0009 inch on the bearing and the shaft respectively, and let the allowance be 0·0009 inch. Then the diameter limits will be as follows :—

(*a*) On the unilateral system.

For the bearing—

3″+0·0018″ and 3″+0·0000″, *i.e.* 3·0018″ and 3·0000″.

For the shaft—

3″−0·0009″ and 3″−0·0009″−0·0009″, *i.e.* 2·9991″ and 2·9982″.

(*b*) On the bilateral system.

For the bearing—

3″+0·0009″ and 3″−0·0009″, *i.e.* 3·0009″ and 2·9991″.

For the shaft—

3″−0·0009″−0·0009″ and 3″−0·0009″−0·0009″−0·0009″, *i.e.* 2·9982″ and 2·9973″.

Although the additional calculation is not very great in a single example, it becomes more serious when a number of limits have to be found. By the introduction of more figures it increases the risk of error. It is a complication also that, in the bilateral system, the nominal size is not one of the limiting dimensions.

Another objection which is raised against the bilateral system is as follows. Suppose that as a result of experience it is found that clearances are too small and that it is decided to increase the tolerances of certain parts. As a rule it is found advantageous to keep the tolerance as large as possible on the bored part. Let the tolerance on the bearing therefore be increased, while the shaft is kept the same. On the unilateral system the minimum bearing size will be

as before, and the maximum bearing size will be greater by the increase of tolerance. The mean bearing size will therefore be greater, which is the result desired, and there will be no loss of interchangeability. On the bilateral system the increased bearing tolerance will be distributed equally above and below the nominal size, so that the mean size will remain the same as before. But as a result of the increased tolerance, some bearings may be smaller than before. Therefore a shaft made to the original limits may now interfere with some of the bearings although the average clearance for a series of fits will remain the same. In order to obtain the desired result of increased average clearance it will therefore be necessary to alter the shaft limits. Complete interchangeability between parts made before and after the change of tolerances would be sacrificed if that were done.

It would, of course, be possible to obtain the desired extra clearance on the bilateral system by an alteration of the shaft size while leaving the bearing unchanged. Interchangeability would not be lost by this method, but the advantage of an increased hole tolerance would not be gained. In this connection it should be remembered that shafts are more cheaply kept within a small tolerance than holes are, at least in the smaller sizes which are commonly finished by fixed reamers. The larger the tolerance the greater is the amount of wear permissible before a reamer must be scrapped. It is assumed that the reamer is initially made to the upper limit of size.

Reamer Sizes

Incidentally, one of the arguments in favour of a modified bilateral system is based on reamer sizes. In this argument it is assumed that reamers are made initially to a standard amount above the nominal size, which is usually less than the tolerance permitted. From this it is deduced that on the unilateral system a reamer must become useless after having worked through only a fraction of the tolerance, whereas on the bilateral system it would continue to work below the nominal size until the lower limit of tolerance had been reached. The argument is correct so far as it goes, but it omits the probability that reamers would be made suitably oversize if the unilateral system were generally adopted. In fact, there would even now be little difficulty in obtaining reamers which would take full advantage of the B.S.I. tolerances. In 1931 the B.S.I. issued a specification for reamer tolerances.

The unilateral system so far discussed has been based on the hole as the invariable member with the tolerance all on the upper side of the nominal size. But it is possible to devise a unilateral system in which the nominal size of the hole should be the upper limit, tolerances would then tend to reduce the size of the hole. Such a system is said to be in use by a number of firms in the U.S.A. Except that it permits the use of reamers initially of standard or nominal size, it is difficult to see what advantages can be claimed for it. There is the very real disadvantage that variations of tolerance directly affect the minimum clearance and therefore necessitate variation of shaft size with consequent loss of interchangeability. The point has already been mentioned in connection with the bilateral system, but it appears in an exaggerated form in the unilateral system where the nominal size of the hole is the upper limit, that is, where the nominal size represents the minimum metal condition.

Those firms which are working with Whitworth standard plug gauges are really working to a unilateral system on the hole basis, since they adopt the convention that a hole is of a certain nominal size when it will just admit a plug gauge of that size. When they work to the plug gauge they permit more or less tolerance according to the slackness or tightness of the fit. Shaft dimensions are then made equal to the plug size, minus or plus a suitable amount for clearance or interference fits respectively. Firms working on this system would have little difficulty in adopting the B.S.I. system of limits. They would merely need to find out what tolerances and allowances they were using and to what classes of B.S.I. limits their tolerances corresponded. Interchangeability of parts made before and after the adoption of the B.S.I. system should present no difficulty.

Arbitrary Nature of Original Tables of Limits

The limit systems first devised followed practice very closely, but they depended on tabulated values for their use. That is to say, they were not reducible to a general statement or expression from which a given class of tolerance or allowance could be obtained to suit any specified diameter. This was a disadvantage if tables were not available or if those at hand were not extended far enough to cover the required diameter. In such cases values had to be fixed without a definite guide, and the results obtained by different individuals by this method might easily fail to interchange. But although the early systems were somewhat arbitrary and irregular it was found

that they all agreed very fairly with a common law. In the discussion of this law which follows the word allowance is most frequently used, but it may be taken that as a rule the tolerance varies with the allowance.

The B.S.I. System of Limits

Experience shows that the allowance for any particular class of fit must increase with the diameter. In the paper on Limit Gauging already mentioned, the following general expression is given to cover all classes of fit.

Allowance $=a+b\sqrt{d}+cd$, where a, b and c are constants whose values depend upon the class of fit, and d is the diameter considered. For clearance and transition fits the constant c is found to have the value zero, so that the third item in the expression vanishes. For the heavier classes of interference fits the constants a and b vanish, so that there remains a quantity which varies directly as the diameter. This is the relationship usually adopted for shrink fits. Leaving this for the present, the remaining classes may be provided for by suitable values of the constants a and b. The constant a is found to be needed to ensure that the allowance shall not fall below a necessary minimum value for very small diameters, for which the second term, $b\sqrt{d}$, might become uselessly small.

The relationship, allowance, $=a+b\sqrt{d}$, may be taken to express generally the experience summed up in the earlier limit gauge systems and the more recent measurements made by the British Engineering Standards Committee and Association. But, in practice, the expression would be inconvenient in the form given, because it would involve a change in the value of the allowance for every change in diameter. This would be a needless complication and is avoided by using one allowance for a range of diameters. In the early systems the ranges of diameters and allowances seem to have been chosen somewhat at random. Although conforming in a general way to the expression given they could not be represented by any simple expression. As already pointed out, this was objectionable if the tables or diagrams were not at hand or had to be extended. The differences which crept into the systems as a result of extension by different people without a common rule were troublesome and were expensive to rectify.

Bearing in mind these points, the Engineering Standards Association, in devising the system to be recommended by them, founded it on a simple relationship between the allowances and the range

of diameters so that it may easily be used without the aid of table or diagram. There is no limit to the diameters covered, hence no difference of opinion can arise by two users extending it beyond the range of the tables at hand. Such extension or the calculation of any required value requires merely the use of suitable values of the range factor, and of a simple formula for the size multiplier. The products of these will give the amounts to be added to or subtracted from the nominal size in order to find the limiting values of the two members. There are two values of the range factor for each member for each class of fit. For the fits most commonly required there is little difficulty in memorising the necessary range factors. The size multiplier is found from the expression $m(m-1) > 20d > (m-1)(m-2)$

where m=size multiplier, always a whole number.

d=nominal diameter in inches.

This system which was devised by Mr. Hedley Thompson is explained in detail in the Proceedings of the Institution of Mechanical Engineers, 1920, Vol. 2. It is the foundation of the recommendation of the British Standards Institute. In the table below are given a series of the range factors by which this system provides for various classes of fits. It will be noticed that there is provision for both unilateral and bilateral hole tolerances. By the choice of suitable range factors for the shaft to pair with any particular hole, it is possible to obtain any desired fit, whether the hole tolerance be uni- or bilateral. For most running fits it makes but little difference which way the hole is specified. But for transition fits it would be necessary to choose one class of shafts for bilateral holes and another class for unilateral holes, as classes K and B, respectively.

RANGE FACTORS PRESCRIBED BY THE BRITISH STANDARDS INSTITUTION

For Unilateral Holes

Class	B.	U.	V.	W.
Range Factor . .	+0·1 0	+0·2 0	+0·4 0	+0·8 0

For Bilateral Holes

Class	K.	X.	Y.	Z.
Range Facto . .	±0·05	±0·1	±0·2	±0·4

For Shafts

Class . .	F.	B.	K.	P.	M.	Q.	TT.
Range Factor	+0·4 +0·3	+0·1 0	+0·05 −0·05	−0·05 −0·15	−0·1 −0·2	−0·15 −0·3	−1·2 −2·0

The unit for the range factors given above is one-thousandth of an inch.

As a rough guide to their application the following may be used :

B holes and P shafts .	Running fit for fine work.
U ,, ,, M ,, .	Running fit for good work, high speeds.
U ,, ,, Q ,, .	Free running fit for engine building.
U ,, ,, F ,, .	Driving fits.
B ,, ,, B ,, .	Sliding push fits.
B ,, ,, K ,, .	Sliding push fits.

The transition fit is usually the most difficult class to manufacture, since the latitude is smaller than is allowed for running or interference fits. The most exacting transition fits may involve some sacrifice of interchangeability, as occurs when parts must be selectively assembled. Fortunately no provision need be made for wear in the transition fit, and the whole of the permissible variation in size may be taken for tolerance. Thus in most cases interchangeable fits can be relied upon.

The interference fit is somewhat complicated, since the allowances depend upon the form and dimensions of the parts. It is difficult to devise a standard system to cover all cases. The B.S.I. has, however, included some ranges of shafts suitable for interference fits.

The B.S.I. allowances for interference fits are based on a parabolic relationship between allowance and diameter. But, under given constant conditions as regards the material and the proportions of the parts concerned, the allowance should vary in a fixed ratio with the diameter, if the stress in the material is to be constant for all sizes. An allowance of one to one and a half thousandths of an inch per inch of diameter is very commonly used, and gives rise to a stress of 12 to 13 tons per square inch in a hub of forged steel of ordinary proportions.

The following examples show how the B.S.I. interferences classes U and F differ from those obtained by a rule such as one-thousandth of an inch per inch of diameter. The interferences are expressed in inches.

Diameter . .	1″	2″	3″	6″	9″
B.S.I. interference varies between	0·0024 0·0006	0·0028 0·0007	0·0036 0·0009	0·0048 0·0012	0·0056 0·0014
0·001 per inch .	0·001	0·002	0·003	0·006	0·009

For many purposes the difference is not great enough to matter, but where an interference fit is used to transmit a twisting effort

from one part to another without the aid of any keys the second rule is better. Variations in the radial thickness of the hubs make a great difference to the strength of the grip, and when the maximum grip is required it is advisable to calculate each case separately.

In an article on Machinery of February 27, 1930, F. H. Roberts gives a nomograph based on Lamé's formula, relating the shaft diameter, hub thickness and torque per inch length of shaft. This nomograph shows very plainly that for a given shaft diameter the grip depends very much on the hub thickness.

For the shrinking of tyres on wheel centres an allowance used by one railway is ($\frac{17}{16}$ D+10) thousandths of an inch, where D is the diameter of the wheel in inches. Such a rule as this is not required to include very small diameters, and through its working range it is very similar to the parabolic rule of the B.S.I.

There is a growing tendency to use shrink fits as a substitute for keyed fits. The best driving effect in a shrink fit is obtained by an interference sufficient to cause a stress very near the elastic limit, but not exceeding it. If the elastic limit should be exceeded there will be a permanent set and some loss of grip. For this reason some engineers consider that keys do not [illegible] a fit as simple shrinkage, because the irregularities [illegible] associated with key-ways cause concentrations of stress and local yielding. Reversing drives, as in rolling mill pinions, especially are found to remain firmer without the aid of keys.

Experiments carried out by Robert Russell, and described in a paper read before the Institution of Mechanical Engineers, show that the condition of the mating surfaces in regard to lubrication is of very great importance to the tightness of an interference fit. Thoroughly clean surfaces not only required much more force to assemble them, but they required also much more force to separate them than did slightly oily or moist surfaces. The method of assembling appeared to be of little consequence in comparison with the state of the surfaces. In one test with the pieces very carefully cleaned, it was only possible to separate them by tearing the metal; parts of one member adhered to the other. Both members were of mild steel. Similar pieces with the same interference but with an oily film were assembled and separated with much lower pressures and the metal was not torn on separation. The pressure was found to depend very much on the kind of oil used. Rape or sperm oil gave very low values which were fifty to sixty per cent of those

given by other oils. The quality of the surface had less effect than its truth, within the range of qualities tested. Ordinary tool marks in the form of a shallow helical groove appeared to alter the grip but little in comparison with that of a smoothly finished surface. But any defect, such as out of roundness or lack of straightness, very definitely affected the security of an interference fit.

A very interesting development in connection with interference fits is the application of solid carbon dioxide to chill the inner member, thereby causing shrinkage which will permit the parts to be assembled. The I.C.I. have devised a method of cooling a double bath of trichlorethylene (freezing point $-123°$ F.) with the carbon dioxide. This liquid transfers the heat from the component to be cooled. The temperatures reached are low enough to reduce steel and cast iron 0·0009 inch per inch of diameter, and brass 0·0015 inch per inch. Where this is insufficient the outer member may be raised in temperature by immersion in a bath of hot water.

CHAPTER XVII

EXAMINATION OF MACHINES AND ATTACHMENTS

THE work done by machine tools is very largely a copy of the forms which are originally put into the machine, and certainly errors which exist in the machine may be reproduced in the work which it does. Errors may arise from several causes. The machine parts may not have been made correctly in the first place; the machine, although correctly made, may have been twisted or pulled out of truth by faulty or weak foundations; the machine may be weakly built so that, although it may appear to be correct when it is not in use, the forces inseparable from cutting will deform it. In some machines, particularly those of the larger kind, the machine frame is not designed to be stiff in itself. The foundation is a necessary part of the structure in such cases and is made of great weight. The truth of the machine depends very much on the way it is aligned and set up on its foundation. Slide ways machined on massive and apparently rigid castings can be twisted seriously out of alignment by uneven supports. Planing machines especially should be tested at regular intervals, otherwise the settlement of foundations or the loosening of shims may make it impossible to do correct work in them, and the cost of rectifying badly planed parts will far exceed that of periodical inspection.

Three-Point Supports

Some machines of the smaller kind are designed and mounted so that they are independent of their foundations. Automatic screw machines, for example, are sometimes made with a rigid box-section type of bed. This is supported on the stand or base by three ball feet clamped in spherical sockets. The clamps are designed simply to hold the feet in place without exerting any straining action on them, so that although the under frame rests on four feet in the usual way and may be twisted by uneven supports, it cannot transmit any twist to the bed. Especial care is desirable in automatics and similar machines of the turret lathe pattern, because twist in the bed is exaggerated in its effect on the alignment of the tools and the

work. But in using any machine tool, care in setting up and periodical inspection are well worth while.

Classes of Tests for Machines

There are two classes of tests applicable to machine tools. One, which may be called direct, involves measurements of the relative positions of the machine parts in their various settings. The other, or indirect type, is made by measuring sample pieces of work which have been machined on the tool. They cannot, either of them, cover the whole field, because the first kind test the machine in the unloaded condition and the second kind test it under load. Some tests of each kind will be described. Some specifications for the accuracy of machine tools make allowance for the probability that the machine will yield slightly under load, and a small initial setting in the opposite direction is prescribed. The possibility of wear is taken into consideration in the same way, so that as wear takes place the parts may become nearer to the ideal.

Many machine tool makers will supply a certificate of inspection with their machines, which gives a record of the results observed during its final inspection at the works. As a consequence of this practice, certain tolerances have become almost standard.

Lathe Tests

Since the lathe is the most common machine tool, the tests which are applied to it will be discussed at some length. Many of these tests are applicable to other machines, but where other tests are needed for the examination of a machine they will be added. In any series of tests, undertaken with a view to the rectification of errors if found, a systematic method of procedure, devised to avoid the need to change adjustments once made, should be adopted. The bed, as the part upon which all others are fixed or guided, should be examined first in any thorough test, especially in respect of levelling and absence of cross-wind. If the machine is a large one it will be advisable to test its alignment horizontally. A fine wire stretched between brackets at the ends of the bed will give a straight line when observed from vertically above. With the aid of a microscope carrying a finely divided scale reading to 0·0005 inch in the eyepiece, this wire is viewed and its position with regard to the bed is observed. The microscope is mounted on a simple bracket of suitable form to

take up a definite position on the machine bed. The base of the bracket is made to suit the design of the bed. For an inverted vee-type bed it may be made with a vee and a flat. For a flat top design a flat base, with a downwardly projecting flange to make contact with the vertical guiding edge of the bed, is suitable. By means of a series of readings the alignment of the bed is compared with the straight line of the stretched wire.

The stretched wire is not applicable to alignments in the vertical plane, since there must always be some sag no matter how tightly it may be stretched. Straight edges and levels are generally used for this test, although optical instruments have been devised and are coming increasingly into use. Optical devices make use of a beam of light for their alignments. Some of these arrangements are described on p. 84.

The test by means of a straight edge is carried out in the case of flat top beds by resting the straight edge on tissue paper feelers at a number of points. The papers should be held at each contact. If the bed has inverted vees, vee blocks having the vee finished parallel to the top and at a constant distance are placed at convenient distances on the vees, and the straight edge is placed on them with tissue paper feelers to indicate contact. Overlapping tests on adjacent lengths enable the examination to be continued beyond the length of the straight edge.

Tests such as the above for straightness are more suitable to the makers' works than to the maintenance department at the user's works, in that they check items which should be made correct before the machine is completed and assembled. The things which the user is concerned to verify are the levelling of the machine on its foundations and the truth of the motion of its slides as assembled for use. A level of the precision type indicating to ten seconds is very useful for setting machine beds and will thoroughly justify its cost in any but the smallest shops. With such a level the bed should be tested longitudinally and transversely, and levelled as required by wedges under the supporting lugs. The transverse levels should be taken across the full width of the guiding surfaces. Supporting blocks must be used for inverted vee beds, care being taken to apply them in the same way at each end. The transverse levelling is most important, as a bed is very easily twisted by irregular supports, and if there should be any cross-wind it is nearly impossible to turn out true work with it.

Spindle Alignment

After levelling, the tests to be applied are in the first place measurements with a dial gauge on test bars. Consider first the alignment of the headstock spindle with the bed. For this purpose a test bar, ground to fit the socket in the spindle nose, and with a projecting part ground parallel and concentric with the shank, is to be used. It may be of a convenient length to suit the size of the lathe, but if more than, say, 5 inches long it should be made hollow to reduce its weight without loss of stiffness. A bar of about 2 inches outside diameter, $1\frac{1}{2}$ inches inside and 12 inches in parallel length, is a useful size for many machines. The shank will, of course, be made to suit the spindle nose. A bar like this ground on centres will test the truth of the socket in the spindle. A dial gauge in contact with the outer end of the bar should not show a deflection exceeding three-quarters of a thousandth of an inch when the lathe spindle is rotated.

The same bar is then used to test the alignment of the headstock with the ways both vertically and horizontally. For this purpose the dial gauge is held on the slide rest. Vertical alignment is checked by applying the dial gauge above the bar at points near the spindle and near the outer end of the bar. A normal specification for this test is that the bar must not be low at the outer end and may be not more than one-half thousandth of an inch high in 1 foot.

Horizontal alignment is checked by setting the dial gauge horizontally in contact with the bar. The permitted variation is between parallel and not exceeding one-half thousandth of an inch forward at the tailstock end. It will be noticed that the variations allowed are in both cases such that they would be diminished under the conditions of use.

If the socket in the spindle runs out the alignment tests must be made by rotating the spindle so that maximum and minimum gauge readings will be taken in each position. The mean value of the reading in each position must be taken to indicate the true axis of rotation. Reference to the permitted tolerances will show that the eccentricity or faulty alignment of the socket may be great enough to conceal or greatly to exaggerate the actual fault in spindle alignment.

Deviation of the spindle axis from the level of the bed is objectionable for chuck work. Parallel boring cannot be done if the headstock is out of line with the ways.

The tailstock is next to be inspected. The requirements are that the axis must be parallel to the bed and that it must not be lower

than the headstock centre nor more than one-thousandth of an inch higher. This error will be reduced by wear. After testing the truth of the lathe centres, and if necessary correcting them, a parallel bar is mounted on the centres and is tested by a dial gauge carried on the slide rest. Two positions of the dial gauge are used—one vertically over the bar and the other at centre height at one side. The bar used in the test is preferably tubular, and it should be ground parallel on centres. Its length and diameter should be proportionate to the size of the lathe. By taking two sets of readings, one with the tail-stock barrel right in, and one with the barrel fully extended, any defect in its alignment is made obvious.

There remains a further important feature to be examined, namely, the setting of the cross slide in relation to the headstock. Upon the truth of this will depend the possibility of facing a plane surface. As a preliminary test during construction a tee-slotted bar carried by a perpendicular taper shank in the spindle nose is used. The tee-slotted bar provides for carrying a contact stud in various radial positions. In each position a reading is taken against a dial gauge carried on the cross slide, with the bar first in front and then behind the centre. The face of the bar, on which the contact stud is seated, is machined square with the axis of the shank. Therefore if the cross slide is square the dial gauge should give the same reading in all positions of the contact stud. Errors are rectified by scraping the cross slide. When the lathe is assembled, as a final check on the cross slides, a light cut is taken over the surface of the face plate, and its flatness afterwards is verified by means of a surface straight edge and sundry tissue paper feelers. Provided the surface so produced is not more than about three-quarters of a thousandth of an inch convex or concave in 12 inches it may be considered satisfactory.

Tests on Planing Machines

The work which is machined on a planing machine is very greatly affected by the levelling of the bed. It is in fact a very close copy of the general form of the surface in which the ways lie. If the ways dip at diagonally opposite corners so that they lie in a warped surface the work planed on the machine will also be warped. Or, if the ways are tilted upwards at each end, the work will have a concave upper surface after it has been machined. A convex surface can be produced by allowing the ends of the bed to fall slightly. It is not suggested that the curvature produced in these ways is very great,

but it can be great enough to increase very materially the labour of finishing, especially where large areas are concerned. With reference to finishing after planing, if there is any curvature in a machined face it is preferably of the concave form, as metal is more easily removed from the ends than from the middle of a surface.

Levelling a Planing Machine

To level the bed of a planer observations must be made both longitudinally and crossways. For the former, levelling bars are rested in the ways and the beds tested from point to point, along the whole length, starting at the housings and working both ways. In a planer of more than small size there will be a number of wedges, by means of which the level can be adjusted from place to place. When the ways are horizontal longitudinally they will not necessarily be level crosswise. Cylinders of equal diameter, preferably ground, should be placed in the vees at opposite sides. On these a straight edge with parallel upper and lower surfaces is placed to carry the level. Again, beginning at the housings and working both ways, from wedge to wedge, the bed is levelled crosswise. As it is possible that the longitudinal level may have been disturbed by the later adjustments the tests should be repeated both lengthwise and crosswise, until there is no deviation.

Allowance for Weight of Table

The table is usually of very considerable weight, and its effect on the bed and foundation must not be ignored. Therefore the levelling process must be repeated with the table in various positions, so that, if any deflection occurs under the moving load, compensation may be made for it. Dealing first with the lengthwise direction, the spirit level should be placed along the table at a point below the tool box, with the table right forward. Then, moving the table backwards stage by stage, the level is read as it comes over each wedge. Considering all these readings together, the deflections under the table weight can be deduced and appropriate corrections applied by lightening up the wedges as required. After this a retrial may still show some deflection, but these should be less than they were. When they have been eliminated a similar series of tests should be done with the level lengthwise at the forward end of the table, beginning with the table in the extreme backward position and working forwards. When this has been done, it is well to repeat the first series of tests

in case any small change may have occurred as a result of the adjustments at the forward end.

The bed being now level lengthwise under working conditions, the cross level must be checked and corrected with the table in various places. This is done with the level across the table, beginning as before with the table right forward and the level at the back end and moving the table backwards from wedge to wedge. Afterwards the front part of the bed is tested for cross-levelling by placing the spirit level across the front end of the table and moving the table step by step from back to forward positions. When any adjustments are made there is some risk that the earlier settings may be upset, therefore it is advisable to repeat all the tests. Any changes will become successively smaller until they finally disappear. Although this process of approximation may appear to be tedious, it is not so in practice, and the time spent on the adjustment of a planer is well repaid in the reduced cost of fitting.

Setting the Cross Rail

Other adjustments which are important concern the levelling of the cross slide. This will determine whether the work will be parallel in cross-section. The adjustment of the housings is tested by a square resting on a plate placed across the ways. By placing the square across and along the bed, the housings are tested in both directions. This test should have been made at the works and the setting determined finally by keys and dowel pins. But the cross-rail does not depend upon the vertical guides on the housings for its position. The length of guide is too short for this purpose. The setting of the cross-rail depends upon the two elevating screws which are both driven by bevel or spiral gears from a common transverse shaft. At some point in this shaft there is provision for changing the angular position of the gears relatively to each other. This is very often a pair of coupling flanges with slotted holes.

In order to test the cross-rail the level is placed upon it and an observation made after raising the rail. It is essential to test after the rail has been lifted, so that the backlash in the screws may be all in one direction, otherwise there is some risk that the rail may stick at one side and may fall freely at the other. The same precaution should of course be taken whenever the rail is reset to a different height. It should always be brought to its final position in the upward direction.

If the rail is found to be out of level the coupling of the transverse shaft must be released and each end of the rail set up by its own screw. When the setting appears to be correct the coupling must be refixed. Trials should be made in several vertical positions of the rail, and if there are any serious differences an average setting of the coupling which will give the minimum error must be selected. In good machines the pitch of the elevating screws should be correct within one-thousandth of an inch per foot.

The Universal Milling Machine

Since the universal milling machine has more adjustments than other milling machines, a discussion of the tests and adjustments will include most of those necessary for the others. The motions of the table of the universal machine are (1) vertical; (2) horizontal, parallel to spindle; (3) horizontal, in any direction up to 45° on each side of the perpendicular to the spindle. This latter motion is obtained by means of a saddle divided horizontally and having the two halves spigotted together.

The alignments of the various slides are measured with reference to the axis of the spindle by means of a dial gauge with holders and squares. The general method of testing these alignments follows the principles outlined in connection with the lathe. The permissible tolerances for errors in alignment are usually about three-quarters of a thousandth of an inch per foot. They must always be in such a direction that they will be diminished by the normal use of the machine.

There is one rather important setting which is peculiar to universal milling machines. The vertical axis, about which the upper part of the saddle and the work-table swivel, must intersect the axis of the spindle in all positions of the saddle. This is of great consequence in cutting helices, because the line of work centres is set centrally with the cutter before the table is swivelled out of square. If the vertical axis of the spigot lies to one side of the spindle axis the centre of the work will be displaced from its correct position under the cutter when the table is swivelled to the angle of the helix. For the same reason the tee slot, in which the spiral head is set, must be in such a position that the line of centres of the head and tail centre is vertically above the axis of the spigot of the saddle.

In order to test the positions of the various axes mentioned, a cylindrical test plug should be clamped to the table with its axis

vertical and concentric with the axis of the spigot. It then remains to be seen whether that plug is vertically and centrally below the cutter spindle, and also below the work spindle. This can be done with some suitably designed holder with a dial gauge so arranged that the position of the cutter spindle may be taken with reference to the plug which is in line with the spigot. The same kind of attachment would enable the position of the spigot with reference to the axis of the work heads to be measured. If the plug when set by the spigot is found to be vertically below the cutter and the work spindles, the setting is correct. If it should not be correctly placed, the error may be due to faulty design, or, more likely, to displacement of the slides by wear.

Turret and Capstan Lathes

The tool-holders and tool-sockets on turret and capstan lathes are very important, and the tool-sockets should be so placed as to be in line with the spindle. A dial gauge carried on an overhanging bracket from the cutter spindle and rotated in contact with a cylindrical bar fitting the tool-socket will serve to check the concentricity of the spindle and socket. By taking readings at two positions longitudinally the alignments of the socket may be tested also. In hexagon turrets the sockets for centring the tool-holder bases should be concentric with the work spindle, and the turret faces should be square with the work spindle when in the operating position. Both these features may be tested by means of a dial gauge carried on a rotating arm from the work spindle.

Turret Indexing

If the test of the tool-sockets for concentricity with the spindle be repeated in each of the turret positions, it will check also the indexing of the turret.

The Pitch of Lead Screws

The pitch of lead or feed screws may be tested by several methods. The screw may be removed from its machine and tried in a special pitch measuring machine, where its pitch can be compared with that of a screw of known accuracy or, with the aid of a microscope, with the graduations on a standard scale. This plan is not often convenient on account of the comparative rarity of pitch measuring

machines of suitable size. A second plan is to cut a sample vee screw with the lead screw to be tested and to inspect this sample screw in a pitch measuring machine. The whole length of a lead screw is not usually examined by this method, which is commonly adopted when it is desired to verify or select portions of a lead screw of sufficient accuracy for some particular job, such as cutting screw gauges. The sample screw need not be of any particular profile, but it must be cut with a single point tool, and it must be cleanly cut with smooth flanks. The cutting of a sample screw tests several items beside the pitch of the screw. This point is discussed rather more fully in Chapter X, but it may be said briefly that the mounting of the screw and errors in the change wheels sometimes have a serious effect.

A third method of testing the pitch of a lead screw is to take measurements of the position of the saddle as it is traversed by means of the lead screw. Before doing this the truth of the thrust collars should be examined by a dial gauge in contact with the central part of the end of the screw (see Fig. 143). When the collars have been examined and, if necessary, corrected, a large change wheel should be placed on the lead screw with an index mark or index pin near the circumference. If the wheels are known to be of good quality it may be more convenient to rotate the screw by gearing from the headstock spindle, because the mechanical advantage assists in making fine adjustment. Careful measurements of the saddle positions are next required. For this a set of end blocks and a good dial gauge are convenient. The dial gauge need only read up to, say, one-tenth or one-twentieth of an inch. An open scale and reliable readings to one or two ten-thousandths of an inch are of more importance than a wide range. This gauge should be attached to the saddle to form one contact point. The other contact point should be fixed to the bed of the lathe so that a series of end blocks can be supported on the bed between the two points.

Starting with a suitable series of blocks to cover the length of screw to be tested the saddle is brought up by rotation of the lead screw until the dial gauge shows definite contact about the middle of the scale. At this time the index mark is fixed at a convenient place to register with the large wheel on the lead screw. If it be desired to test the screw at complete pitch intervals only, the end blocks are diminished by the amount of one nominal pitch. The screw is rotated once and the new reading of the dial gauge is observed. The

difference from the previous reading indicates the error, plus or minus, in the pitch of the screw at the point observed. Proceeding in this way a complete record of the screw can be obtained.

By using fractional rotations and removing the appropriate gauge block each time the screw may be examined as fully as desired.

As an alternative to the use of end blocks, a microscope with cross web and a scale may be employed, but usually it is easier to obtain the gauge blocks than to obtain a sufficiently good scale in the ordinary engineering workshop.

Lead screws are commonly guaranteed to be within an error in pitch not exceeding 0·001 inch in 12 inches.

Dividing Heads and Rotary Tables

Tests on dividing heads at the makers' works are often done by means of a large diameter (12 inches) disc mounted truly on the work spindle and observed with a microscope with micrometer adjustment. The spindle and disc are indexed by the index plate in the usual way. Variations from the nominal angle of rotation are measured by the micrometer adjustment of the microscope.

Index heads of the ordinary pattern, actuated by a crank on the worm spindle and set by the holes in an index plate, are guaranteed by some makers not to exceed an error of seventeen seconds, or roughly, one-thousandth of an inch at 6 inches radius. Many of the heads in use do not approach this accuracy.

The optical head is described on p. 163.

Rotary tables, which are ordinarily set to the required angle by a direct reading graduated circle of moderate diameter are limited in their accuracy by the possibility of subdividing the graduations. As a rule, from thirty to ten minutes is the limit of accuracy for this kind of accessory, although finer subdivision is possible if the operating worm is fitted with a micrometer collar. Too much reliance should not be placed on the subdivision possible by this device, because it often exceeds the truth of the worm-wheel, upon which in the end the division must depend.

The rotary tables fitted to machines of the jig-boring class are of very much higher grade than the ordinary table fitted to the general run of machines. In one table of this kind a specially accurate worm gear is fitted, and the table can be set by a vernier on the worm to one second.

In another the limit of error is specified as less than six seconds.

Observation of Moving Parts

The tendency to use higher speeds in machining processes has made it very desirable to be able to observe what actually occurs under these high-speed conditions. The need for direct observation is the greater because the behaviour of machines at low speeds is usually very different from that at high speeds. Forces which are negligible at low speed become rapidly greater as the speed is raised, and before long they may become the controlling factor which determines whether the machine will work or not. Methods of lubrication must be designed with very careful attention to the effect of speed, or it may be found that the lubricant never reaches the surface which need it. The behaviour of petrol motor valves and springs is very greatly influenced by the rate of working. The solution of problems connected with both these items has been assisted by the ability to observe rapidly moving parts. The effect of speed on the formation of a shaving has already been mentioned (p. 41). Fortunately many of the moving parts which may have to be observed move in regular cycles, so that by suitable interruptions of vision a certain part may be selected from each of a long series of cycles thus giving time for complete examination. Or, by gradually changing the period of observation in relation to the cycle the effect of slowing down the operation is produced. That is to say, by delaying the period of vision to a time slightly later in the cycle the complete sequence of events is seen in a time equal to that required for the periods of vision to pass from one end of the cycle to the other.

There are two methods in use for causing interrupted vision. One relies upon an electric lamp controlled by a switch which may be operated by the moving mechanism or may be operated independently by a variable speed electric motor. The lamp must be of a kind which lights and goes out suddenly, the discharge type, so that the object is definitely visible or invisible.

Another type of apparatus employs a special design of rotating shutter to interrupt the sight. This shutter is driven by some form of motor which may be varied in speed. A clockwork motor is employed in one, an electric motor in another and an air turbine driven by a hand-operated bulb in another. Each of the three has its own advantages, and very useful data have been obtained by all.

It may be remarked that so long as the moving parts follow a repeated sequence of movements it is not necessary that the interruptions should exactly synchronise with the motions. Differences

in periodicity merely produce the effect of more or less slow motion. Exact synchronism enables the parts to be observed as if they were constantly in one part of the cycle of operations. Many of the actions, which occur in the course of machining, are of a cyclical nature. It is therefore likely that the introduction of conveniently portable stroboscopes, together with the increasing speed of machining operations, will greatly extend the application of this method of observation to workshop processes in the near future.

Necessity for Good Balancing of Rapidly Moving Parts

The problem of balancing moving parts is very serious, especially in grinding where speeds are high and forces due to lack of balance are correspondingly large. There is no machine frame strong or rigid enough to prevent vibration if the machine includes a rapidly moving and badly balanced part. At one time speeds, apart from grinding, were low enough to avoid trouble except in cases of abnormally bad balance, but the increased speeds frequently used in taking finishing cuts with the carbide type of cutting tools are quite high to induce considerable forces unless care is taken to ensure good balance. No attempt should be made to turn out precise work unless the moving parts of machines and work are balanced before machining is started. Faults may be introduced into the work even though the vibration of the machine may not be very noticeable. A vibration indicator which shows the frequency will often enable the source to be found, when it is usually not difficult to cure the trouble. It is the untraceable vibrations which cause most trouble. A simple indicator is shown in Fig. 1, p. 8.

APPENDIX I

The Measurement of Effective Diameter of Vee Thread Screws

One wire is placed in the groove at one side of the screw and two other wires equal in diameter to the first are placed on the opposite side. A micrometer reading is taken across the screw and the wires. If a support be provided to hold the micrometer so that it is kept perpendicular to the screw, one wire only at each side of the thread is sufficient.

For a symmetrical vee thread, the effective diameter is the diameter at half the depth of the thread. What may be called the ideal cylinders or wires would make contact with the thread at the half depth. Since this ideal diameter is sometimes not easy to obtain, another diameter may be used which may touch the flanks of the threads at a slightly greater or less depth, as the wire is of less or more than the ideal diameter.

Let R=measurement over the wires on opposite sides of the screw.

θ=angle of vee thread.

p=pitch of thread.

D=ideal diameter of wire$=\frac{p}{2}\sec\frac{\theta}{2}$.

d=diameter of wire actually used.

Then the distance from the centre of the ideal wire to the centre of the wire used$=\frac{1}{2}(d-D)\operatorname{cosec}\frac{\theta}{2}$, and, the depth from the centre of the ideal wire to its point of contact with the thread, measured perpendicularly to the screw$=\frac{D}{2}\cdot\sin\frac{\theta}{2}$.

Subtracting twice the sum of these two quantities together with the diameter of the wire used from the micrometer reading, R, the result is the

$$\text{Effective diameter}=R-d-(d-D)\operatorname{cosec}\frac{\theta}{2}-D\sin\frac{\theta}{2}$$

$$=R-d\left(1+\operatorname{cosec}\frac{\theta}{2}\right)+\frac{p}{2}\left(\frac{\operatorname{cosec}\frac{\theta}{2}}{\cos\frac{\theta}{2}}-\tan\frac{\theta}{2}\right).$$

$$=R-d\left(1+\operatorname{cosec}\frac{\theta}{2}\right)+\frac{p}{2}\cot\frac{\theta}{2}$$

For the Whitworth form of thread, where $\theta=55°$, this expression is equal to $R-d(3{\cdot}16568)+p(0{\cdot}96049)$.

APPENDIX II

Note on the British Standard System of Limits and Fits for Engineering

In this system the whole range of work diameters is divided into a series of smaller ranges, which form an arithmetical series of the form 0·1, 0·2, 0·3, 0·4, and so on up to any desired value. For each range, for any particular class of fit, the allowance is a constant quantity. The allowance increases with diameter in such a manner that from one range of diameter to the next the increments of allowance are equal throughout the whole series.

If such a relationship be plotted with allowances as ordinates and diameters as abscissæ, then a stepped curve will be formed, and it will be found that the centre points of the steps will lie on a curve of the form $A=a+b\sqrt{x}$, where A=allowance, a and b=constants, and x=0·1 inch.

This expression is the general relationship between allowance and diameter for clearance and transition fits and is often used for interference fits also. The stepped outline represents the practical modification which is adopted to avoid continuous change of allowance with diameter. Such continuous change would be unnecessary and inconvenient.

From the stepped curve is deduced the expression given on p. **294**.

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